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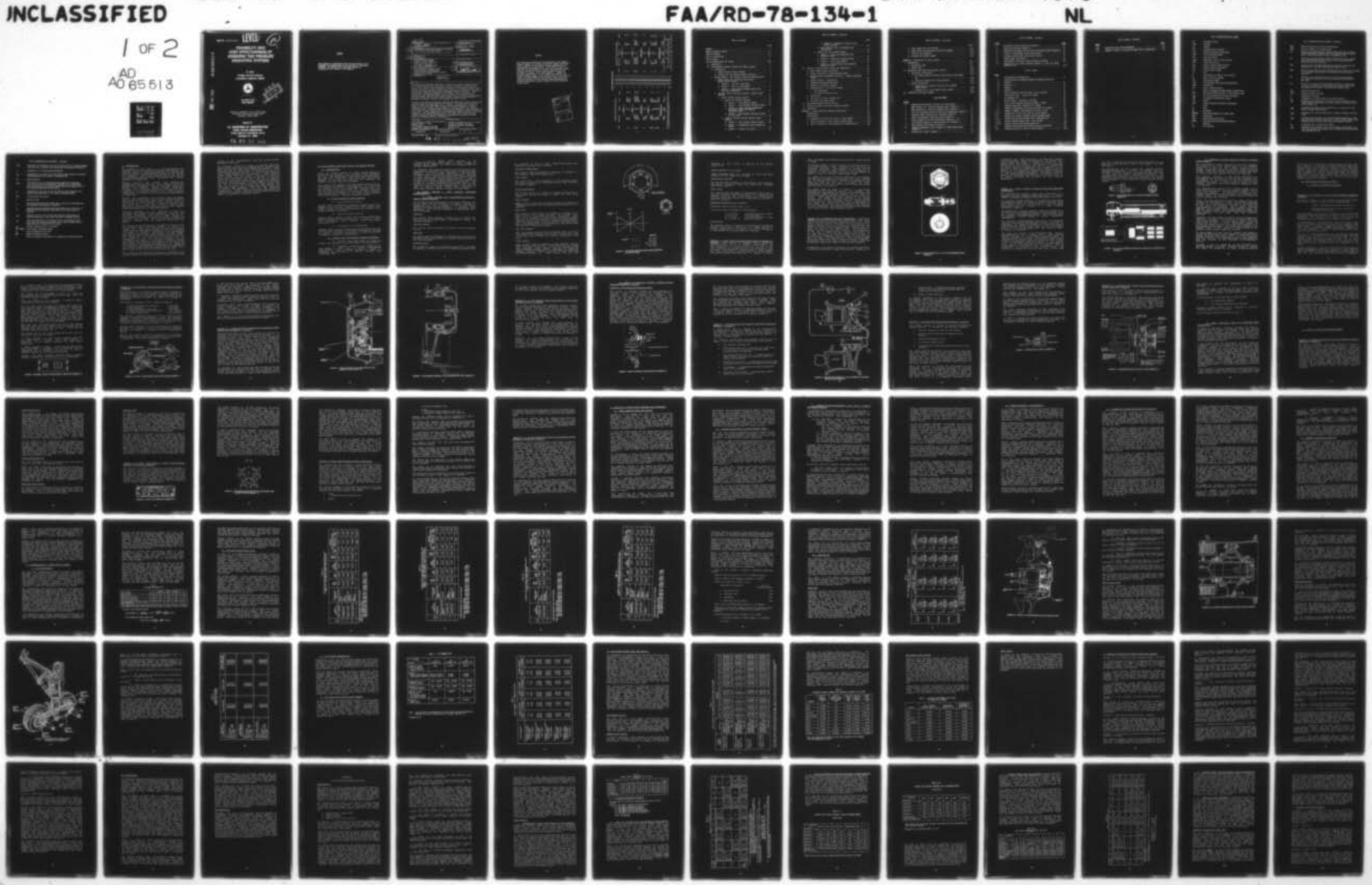

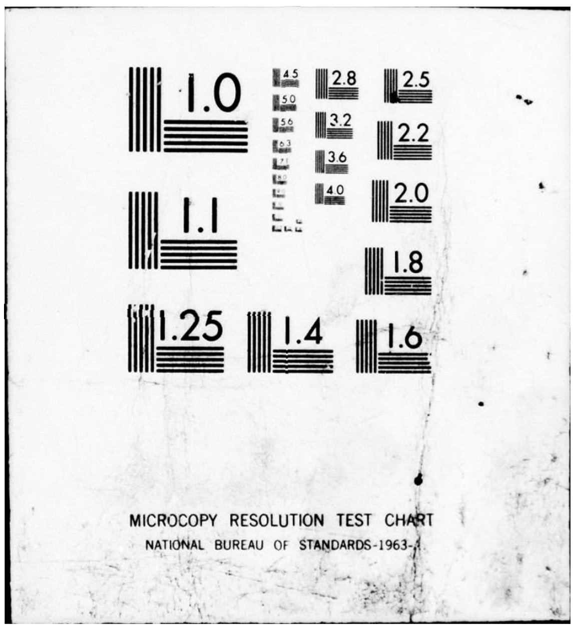
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Report No. FAA RD 78-134,I

LEVEL

FEASIBILITY AND COST EFFECTIVENESS OF AIRBORNE TIRE PRESSURE INDICATING SYSTEMS

R. Suiter

Douglas Aircraft Company

Long Beach, California 90846

OCTOBER 1978

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL AVIATION ADMINISTRATION

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16. Abstract

The cost-effectiveness and feasibility of airborne tire pressure indicating systems are evaluated for potential application to modern air carrier transports having 6, 10, and 18 wheels. Both wheel mounted pressure readout gauges and devices and cockpit tire pressure warning indicators are studied. Typical wheel mounted readout devices and eleven conceptual cockpit indicating systems are discussed. Information on accuracy, temperature compensation requirements, weight, installation cost, system cost, and system maintenance cost is provided. Each cockpit system is evaluated against important design criteria which require that cockpit systems cause no false warnings and that each system be capable of being tested periodically to determine its ability to detect a low pressure tire when it occurs.

A study of tire failures is made for 1973-1976 identifying rate of tire failures and aircraft damage costs resulting from tire failures. The study presents data that shows that 65% of airframe damage cost is related to underinflation - induced or related tire failures which may be avoided by a properly designed tire pressure indicating system. Average airframe damage cost per departure for each study aircraft, based on actual airline data, is presented with comments on delay and cancellation costs. Aircraft damage costs and tire maintenance costs that may be avoided are compared to tire pressure indicating system life cycle costs to show that tire pressure systems are basically feasible, but marginally cost effective aircraft testing of promising systems is recommended.

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PREFACE

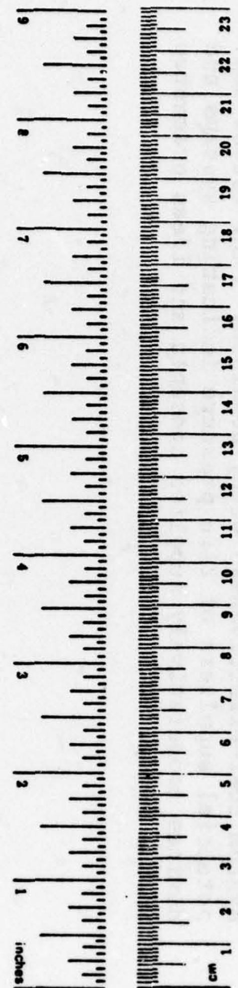
This study was conducted and report prepared by the Douglas Aircraft Company, a Division of McDonnell Douglas Corporation, under a contract for the Federal Aviation Administration of the Department of Transportation. The effort is part of a study for the improvement of aircraft tire operational safety. Technical monitor for Federal Aviation Administration was Mr. Robert C. McGuire, FAA Program Manager. A number of airlines cooperatively supplied valuable tire failure and related airframe damage cost data which made the tire pressure system cost-effectiveness study possible. Many actual and potential suppliers of tire pressure indicating systems and devices cooperatively supplied concepts and ideas presented in the study.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

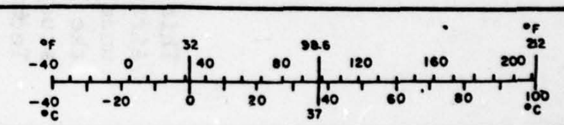


TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

TABLE OF CONTENTS - Continued

LIST OF FIGURES

LIST OF FIGURES - Continued

LIST OF TABLES

LIST OF TABLES - Continued

LIST OF ABBREVIATIONS AND SYMBOLS

AC	Alternate Current
ACFT	Aircraft
AL	Airline
ATP	Acceptance Test Procedure
ATR	Advanced Technical Requirements
BITE	Built-in-Test-Equipment
CPS	Cycle per Second
DR_{TPI}	Delay Rate for TPI Sysyem Failures
EPR	Engine Power Ratio
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FOD	Foreign Object Damage
FT	Feet
g	Acceleration of Gravity (32.2 ft/sec^2)
Hz	Hertz (cycle per second)
IAS	Indicated Air Speed
ICAO	International Civil Aviation Organization
INOP	Inoperative
JFK	John F. Kennedy Airport
K	Ratio of Component Operating Time to Flight Time
KNOT	One Nautical Mile per Hour, or 1.15 mile per hour
λ_{TPI}	The Total Failure Rate for the TPI System
LAX	Los Angeles International Airport
LBS	Pounds
LVDT	Linear Variable Differential Transformer
M	Meter
MI	Miles
MM	Millimeter
MMHR/FH	Maintenance Manhours per Flight Hours
MSEC	Millisecond
MTBF	Mean-Time-Between-Failure
MTBUR	Mean-Time-Between-Unscheduled-Removals
N	Quantity
N/A	Not Available

LIST OF ABBREVIATIONS AND SYMBOLS - Continued

NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
%A	Percent of the undetected TPI system failure rate that is checked for proper/improper operation during an Acceptance Test Procedure (ATP). This is the percent that is in addition to %B.
%B	Percent of the undetected TPI system failure rate that is checked for proper/improper operation during a Built-in-Test-Equipment (BITE) test of the TPI system.
%DA	Percent of the total TPI system failure rate that is detected and annunciated to the flight crew when the failure occurs.
%FW	Percent of the total TPI system failure rate that cause false warnings, i.e. erroneously annunciates to the flight crew a low/flat tire indication.
%N	Percent of the undetected failure rate that is never detected, i.e. undetected failures that are not detected by either BITE or ATP tests.
%U	Percent of the total TPI system failure rate that is undetected, i.e. due to failures in the TPI system that are not detected and annunciated to the flight crew when these failures occur.
PSI	Pounds per Square Inch
PSIG	Pounds per Square Inch Gage
Q	Probability of Failure
Q_D	Probability of a delay caused by TPI system failures
Q_{FW}	Probability per departure of a failure of the TPI system so that a false warning to the flight crew occurs during the critical portion of the takeoff run.
Q_{HAZ}	Probability per departure of a hazard due to a low/flat tire and lack of warning during takeoff.
Q_{MON}	Probability of a false warning due to a monitor threshold tolerance error.
Q_{MWL}	Probability per departure of TPI system falsely annunciating a low/flat tire warning in the cockpit due to the TPI monitor limits being exceeded when no low/flat tire exists (non-hardware failure).
Q_T	Probability that a low/flat tire exists
$Q_{T\&I}$	Probability per departure of TPI system falsely annunciating a low/flat tire warning in the cockpit due to transients and intermittents (non-hardware failure).

LIST OF ABBREVIATIONS AND SYMBOLS - Continued

Q_{TPI}	Probability per departure that the TPI system will not operate properly (not warn) for a low/flat tire during taxi and during the takeoff run
R	Probability of a system operating properly
R_{DA}	Probability of the parts of the TPI system, whose failure is detected and annunciated in the cockpit, working properly
RF	Radio Frequency
R_{TPI}	Probability of the TPI system operating properly per departure, i.e. it will detect and annunciate a low/flat tire to the flight crew from power on the aircraft through taxi-out and takeoff run to the critical-engine-failure speed (V_1).
R_u	Probability of the parts of the TPI systems, whose failure is not detected and annunciated in the cockpit, working properly.
SDR	Service Difficulty Reports
t	Period of time
t_A	Mean-Time-Between-Failures (MTBF) when an ATP test is performed and any existing A type failure is detected.
t_B	Mean-Time-Between-Unscheduled-Removals (MTBUR) when a BITE test is performed and any existing B type failure of the TPI system is detected.
t_{EXP}	Exposure time of concern during which the TPI system should be operating properly, in this case from power on through taxi-out.
t_{OP}	Total operating time of TPI system, since N type failures could occur any time during the operating time of the TPI system without being detected or indicated by any tests.
t_{TO}	Critical takeoff period = 30 seconds.
TPI SYSTEM	Tire Pressure Indicating System
V_1	Critical-Engine-Failure Speed
WBS	Weight and Balance System
Z	Ratio of Component Line Removals to subsequently verified failures.

I INTRODUCTION

The purpose of this study is to evaluate airborne tire pressure indicating systems and devices as a potentially cost effective means of minimizing premature tire removals, and tire failures and attendant aircraft damage, on air carrier jet transports. Both wheel mounted devices such as fill valve/pressure gauges and cockpit indicating tire pressure systems are investigated.

Despite aircraft and aircraft tire manufacturers recommendation to check aircraft tire pressures daily for optimum tire maintenance, this may not always be possible. Aircraft tires, however, require frequent maintenance attention. It is known that any aircraft tire may lose up to 5 percent of its inflation pressure in any 24-hour period. Consequently, the chances of any tire becoming underinflated is significant.

However, the probability is not without cause; for example due to a particular airline route structure difficulty may be experienced in performing daily tire pressure checks or aircraft may return to a primary maintenance facility only once every two to three days. Also, inclement weather increases the difficulty in performing timely tire pressure checks particularly on an 18-wheeled airplane.

Increased awareness of the importance of good tire maintenance has produced tighter maintenance practices with attendant improvements in tire failure rates. The use of a tire pressure indicating (TPI) system or device, however, can facilitate tire pressure checks and could be an effective means of reducing costs and improving operational tire safety.

The intent of the TPI system is obviously to advise or warn of low pressure that occurs after pushback or taxi-out or takeoff roll. With this warning the maintenance and/or flight crew can take whatever corrective action is necessary to prevent the possible consequences of an underinflated tire, namely a tire failure and possible aircraft damage. With this in mind, it then becomes necessary to define what a tire failure is, the cause of tire failures and the consequences of those tire failures in terms of cost and increased hazard exposure. Tire pressure indicating devices and systems are discussed and evaluated in the body of the report and tire failure data and damage costs are summarized in Appendix A. Applicability of TPI systems and analysis of cost of tire failures has been examined for the DC-8, DC-9, DC-10, B-707, B-727, B-737, B-747 and L1011 aircraft.

The purpose of the wheel mounted gauge is to facilitate tire pressure checks by maintenance and by the flight crew on walk

arounds so that underinflated tires may be more readily detected at the ramp.

The potential utility of a cockpit tire pressure indicating system can be appreciated by reviewing typical incidents that have occurred on some major commercial transports. These incidents typically involve loss of pressure in one tire early during the taxi roll due to a tire or wheel failure or foreign object damage such as running over a light standard when turning onto the runway. This early failure is undetected by the flight crew and the takeoff is continued until the overloaded mated tire fails and the takeoff is aborted at high speed with significant damage to the aircraft and risk to the passengers. An early warning to the flight crew of the first tire failure may have avoided the associated damage or greatly reduced the damage and the risk to aircraft and passengers. The cost and additional complexity of systems that can accurately read actual tire pressure may be further justified if they become the accepted means of performing tire pressure checks.

II. TIRE PRESSURE INDICATING DEVICES AND SYSTEM CONCEPTS

A. INTRODUCTION

First, the design criteria for wheel mounted gauges and devices will be discussed with available units described. Two fill valve gauges and one wheel mounted pressure switch with hand held interrogator that have been specifically designed for aircraft are described with tradeoffs and comments on service experience included.

Next, cockpit tire pressure indicating system design criteria is discussed with emphasis on the importance of eliminating all possible false low tire warnings on takeoff roll. The system concepts, very few of which are currently available for aircraft off-the-shelf, are discussed by major category. Eleven systems were included in the study after reviewing over twenty concepts. The major categories include:

1. Direct Pressure Sensing Concepts

a) Analog Pressure Sensing

Systems which can measure and optionally display actual tire pressure in the cockpit via some form of axle coupler that allows reading of tire pressures with the aircraft in all flight and ground conditions;

b) Discrete Pressure Sensing

Systems which provide go-no-go type indication using wheel mounted pressure switches coupling via a magnetic circuit that interrogates switch position once every wheel revolution; and

c) Ultrasonic or RF Transmission

Systems which provide discrete go-no-go indication of a low tire via radio frequency or ultrasonic transmission (although no supplier ultimately proposed such a system for aircraft the general concept will be discussed).

2. Indirect Low Tire Sensing Concepts (Go-No-Go)

a) Systems using Bogie Strain via weight and balance type systems to indirectly detect low tire pressure;

b) Mechanical approaches that attempt to use axle height or bogie tilt to detect substantially underinflated tires (although potentially simple, no discussion was included as no feasible concepts were discovered), and

c) A system which proposes to use differential anti-skid wheel speed to detect changes in rolling radius between two tires on the same gear when one becomes underinflated.

In virtually all cases the concepts are proprietary or have proprietary features which are the property of the particular supplier. To protect these proprietary rights only that information which is generally public knowledge is described in this report. Many of the concepts are covered by patent or patent disclosures. Further, each system has a code or concept letter which is used throughout to avoid implication of ranking of a specific manufacturer's design concept. The airline or airframe manufacturer using this report should, therefore, find it useful as a general guide on the pros and cons of general design concepts when considering or evaluating a specific device or system for their fleet.

B. DESIGN CONCEPTS - TIRE PRESSURE INDICATING SYSTEMS/DEVICES

1. Wheel mounted fill valve/gauge and devices - General Design Criteria.

The following design requirements are general guidelines that may be useful in the selection of gauges, switches or transducers that may be mounted on an aircraft wheel. Specific values may be altered based on a particular users experience. The criteria presented is specifically for a fill valve/gauge.

OPERATION

The article shall provide a valve port to allow tire inflation and an integral gauge to continuously display the inflation pressure.

INFLATION MEDIUM

The article shall be suitable for service with dry nitrogen or air.

PRESSURES

The article shall be designed for 690 psig burst pressure and 460 psig proof pressure based on a nominal inflation pressure of 170 to 180 psig.

OPERATING RANGE

The operating range of the pressure gauge shall be 100 psig to 300 psig. Pointer direction for increasing pressure shall

be clockwise or left to right. Gauge pointer shall have mechanical restraint above 300 psig.

OPERATING TEMPERATURES

The article shall be designed to withstand -65 degrees F to +300 degrees F operating temperatures.

SCALE ERRORS

The scale error from +40 degrees F to +120 degrees F shall not exceed ± 4 psig at the 200 psig set point and otherwise as shown in Figure 1.

TORQUE REQUIREMENTS

The article shall be torqued to a maximum of 200 lb-in on installation and shall not yield or deform with 300 lb-in torque.

GAUGE RESPONSE

Gauge pointer shall instantaneously respond to increases or decreases in pressure due to filling and fluctuations in tire pressures.

GAUGE FACE

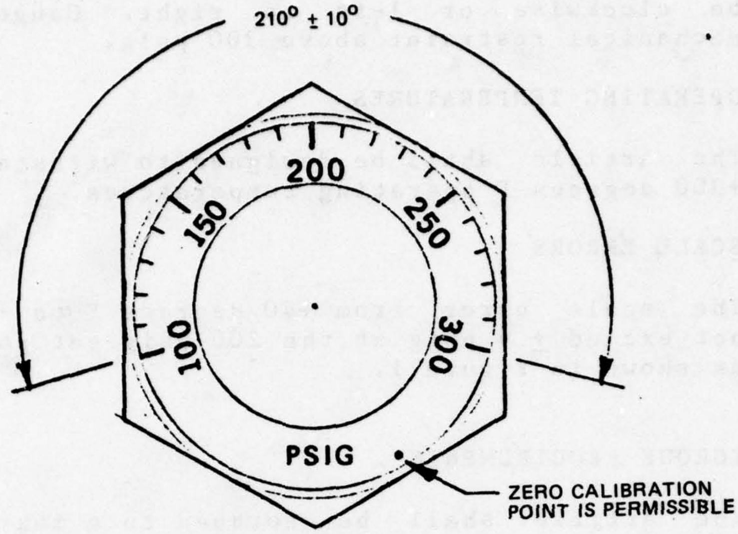
The pointer position shall be legible at a distance of at least two feet. As a design objective, the circular scale shall cover at least 3/4 of the gauge circumference. Gauge face will be mechanically pinned to case to prevent movement. Gauge face may be color coded with acceptable pressure bands, refill and replace bands or may be plain so that gauge may be used interchangeably on nose and main gear tires on the same aircraft and on different aircraft.

FAIL SAFE LEAKAGE

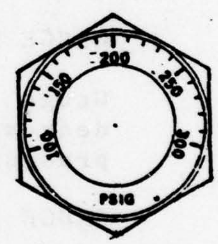
With the pressure sensing device fractured, after one minute the pressure loss should be no more than 5 psi per hour from a 5.24 cubic foot or larger tire reservoir pressurized to 200 psig.

GAUGE CRYSTAL

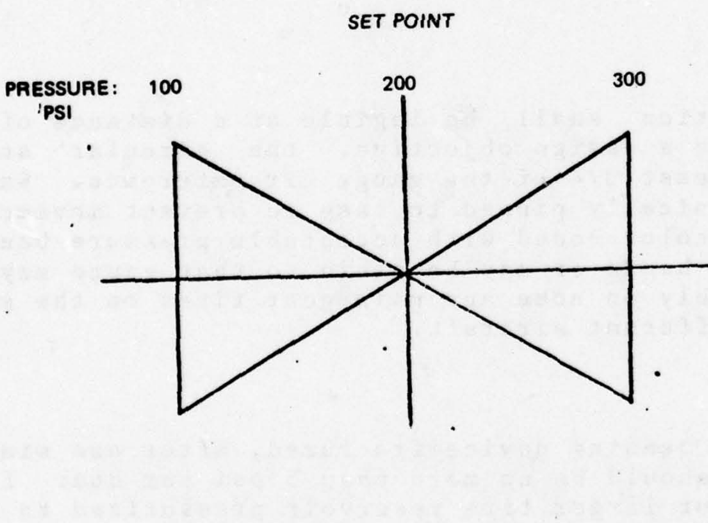
Gauge crystal shall be sealed to prevent moisture, dust and fluid from obscuring the face. Shock loads shall not damage seal interface. Gauge crystal shall be transparent and impact resistant material which is resistant to commercial aircraft cleaning solvents, aircraft hydraulic fluid, and MIL-H-5606 hydraulic oil. Gauge crystal, and vent seal



GAGE FACE
2X SIZE



ACTUAL SIZE



				CONDITION
TOLERANCE: PSI	±5	±4	±5	40°F TO 120°F
	±7	±5	±7	65°F TO 40°F AND 121°F TO 250°F
	±8	±6	±8	251°F TO 300°F

FIGURE 1. TOLERANCE SPECIFICATIONS, WHEEL-MOUNTED FILL/VALVE GAGE

material, if used, should be approved by the aircraft manufacturer.

INSIDE DIAMETER OF FILL VALVE

Gauge mechanism shall not infringe on valve core thread diameter for full length of fill valve.

INSTALLATION POSITION

The article shall be capable of installation in any position, and pointer indication shall not exceed the tolerance specified in Figure 1.

SHOCK LOADS

The article shall be capable of withstanding 100g in each of the three mutually perpendicular planes in a positive and negative direction for a time duration of 11 milliseconds, and shall reach that level in 5.5 milliseconds ± 1 ms. for a total of 18 shocks.

RESONANCE FREQUENCIES AND VIBRATION

Resonances must be greater than 24 Hz

The article shall be capable of withstanding:

5 to 31.3 Hz	.4 double amplitude, inches
31.3 to 51 Hz	20g acceleration
51 to 81 Hz	.15 double amplitude, inches
81 to 1,000 Hz	±50g acceleration

ACCELERATION

The article shall be capable of withstanding accelerations per MIL-G-83016 except acceleration is 1,000g instead of 3,000g, temperature is 300 degrees F instead of 360 degrees F, and pressure is 460 psig instead of 550 psig.

<u>Concept A - Tire fill valve/gauge specifically designed for aircraft:</u> These gauges are designed with a multi-turn helical Bourdon coil as a pressure sensing device. The indicating pointer is attached directly to the end of the coil resulting in a gauge with only one moving part. This construction eliminates all linkages, gears, return springs and other parts subject to wear found in the conventional C tube pressure gauges thus improving its ability to resist

wear and damage from vibration and shock over longer periods of usage.

The helical Bourdon coil has a nominal overpressure factor of 1-1/2 times pressure range. Hysteresis and friction are virtually eliminated. Proportioning the Bourdon coil by using the multi-turn helix results in the reduction of stresses to give extremely long cycle life and enables the gauge to retain its accuracy during normal usage.

The gauge and the fill valve are combined into one assembly and this unit is mounted on the wheel in the port provided for the existing fill valve. The physical dimensions of the gauge are such that the unit is within the wheel configuration and will not interfere with existing structures when the wheel is retracted.

The actual gauge is shown in Figure 2 in one version developed for an airline that desired color banding. The manufacturers gauge design has been service evaluated on Navy F4's and by a number of major airlines with at least one airline already having retrofitted their fleet of 747's and DC-10's. The gauges have been reported to be working satisfactorily and have provided valid tire removal warnings in early service. Once sufficient service experience has been gained the airline may eliminate the requirement to cross check pressures with hand held gauges to take advantage of the maintenance cost savings from reduced tire pressure check times (see cost effectiveness section).

Concept B - an integral tire fill valve/gauge: Specifically designed for aircraft from another manufacturer. This gauge offers a different gauge face arrangement with the fill valve offset from the center of the gauge. The construction of the gauge is similar in that it is a helically wound Bourdon tube sealed at one end with the pointer firmly attached and the other end open to the pressure source. When pressure is applied, the Bourdon tube tends to unwind. The configuration of the tube -- number of turns, diameter, tube shape -- is such that response to the pressure change within the tube is of sufficient magnitude that the pointer will be deflected directly without intervening devices. Thus, a pressure gauge with one moving part and no friction surfaces is achieved. The Bourdon tube of the sensor is made of Inconel X-750 for exceptional temperature, physical and chemical stability.

In addition to the features claimed by the manufacturer which include high reliability, rugged construction, retention of

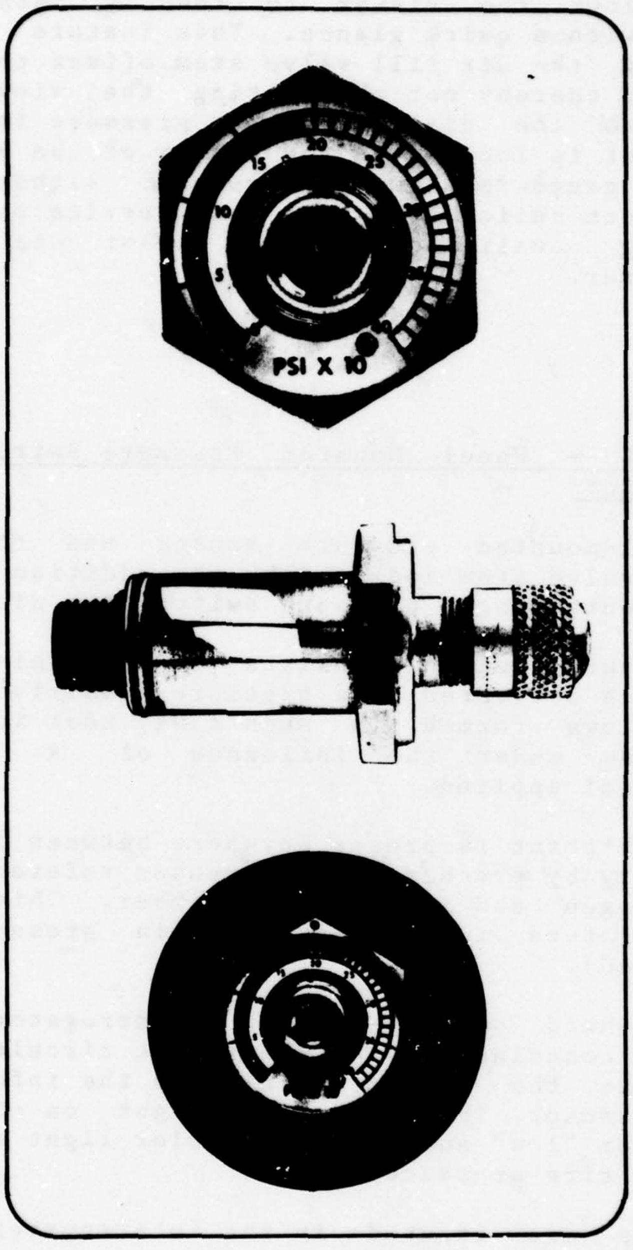


FIGURE 2. WHEEL MOUNTED FILL VALVE/TIRE PRESSURE GAGE—CONCEPT A

calibration with 150% overpressure, and high burst pressure the main advantage claimed is readability. The design of the gauge allows the viewer to readily determine the tire pressure with a quick glance. This feature is incorporated by having the air fill valve stem offset to one side of the dial face, thereby not obstructing the viewability of the pointer to the dial face. The pressure indicating pointer pivot point is located in the center of the gauge. A picture of this gauge is shown in Figure 3. Although this specific gauge is not believed to have been service tested to date it is being qualified by at least one major airframe manufacturer.

Concept C - Wheel Mounted Pressure Switch With Hand Held Interrogator

The wheel-mounted pressure sensor and transponder is a standard valve stem modified by the addition of a reference chamber containing a pressure switch, two diodes and a coil.

The pressure switch consists of a miniature snap action microswitch activated by a pressure sensitive nesting ripple type bellows formed in such a way that it will have large deflections under the influence of a small pressure differential applied.

The switch point is preset anywhere between 50 and 500 psi at the factory by precharging the sensor reference chamber with dry nitrogen and sealing the chamber. This method corrects for temperature induced changes in pressure (temperature compensated).

The hand-held battery-powered interrogator and "LOW/SAFE" indicator contains all the electronic circuits necessary to interrogate the sensor and display the information received from the sensor. The red color light on the interrogator stands for "low" and the green color light stands for "safe" or normal tire pressure.

Two coils are located in the interrogator head. One is a transmitting coil and is excited with a high frequency carrier modulated by a low frequency reference signal. By coupling a third coil (located in the pressure sensor) to the coils in the interrogator unit, and shunting it with a diode, a signal at modulation frequency results in the receiver coil. If the diode polarity is reversed, the phase polarity of the signal in the receiving coil is reversed. This is essentially the function of the pressure sensor. The detector is arranged such that with zero input, both lamps

are off. Input polarity determines which lamp turns on, the green for go and the red for no-go. The equipment is shown in Figure 4.

The manufacturer of this concept has hardware virtually available off-the-shelf. Although the hardware has been evaluated by several airlines, it is believed that there has, to date, been no service experience accumulated. One operator with a large fleet of narrow body twin jets has been considering fitting their fleet with the system and placing the interrogator in the cockpit for flight crew use on walk around.

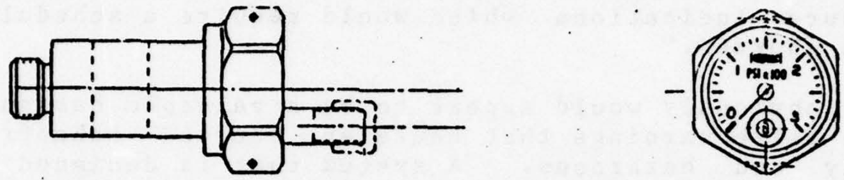


FIGURE 3. WHEEL MOUNTED FILL VALVE/TIRE PRESSURE GAGE – CONCEPT B

HAND-HELD INTERROGATOR/INDICATOR SCANNING UNIT ACTUAL SIZE

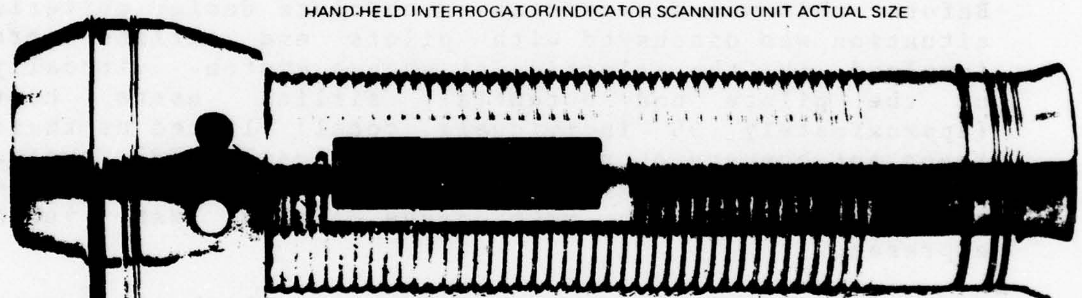
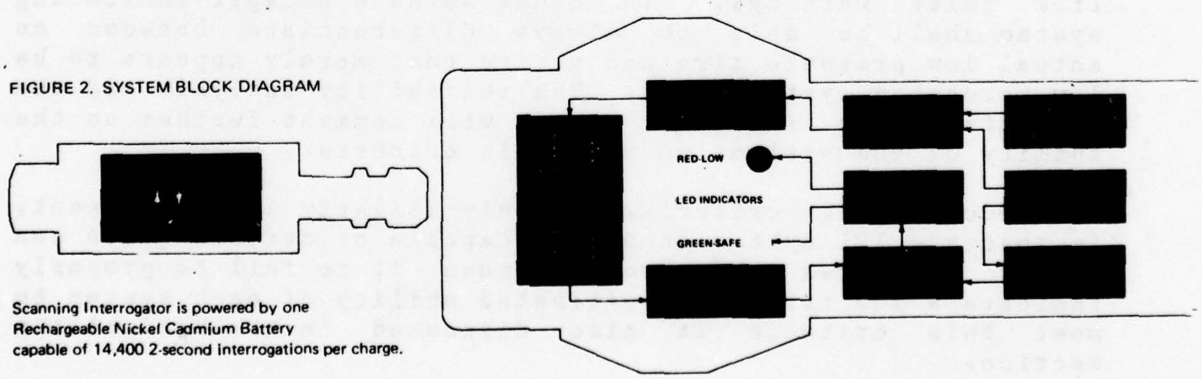


FIGURE 2. SYSTEM BLOCK DIAGRAM



Scanning Interrogator is powered by one Rechargeable Nickel Cadmium Battery capable of 14,400 2-second interrogations per charge.

FIGURE 4. FILL VALVE PRESSURE SWITCH WITH HAND-HELD INTERROGATOR – CONCEPT C

2. Candidate Cockpit Indication Systems - General Design Criteria

The environmental design requirements outlined in paragraph II B1 above for fill valve gauges apply to any component mounted on a wheel for tire pressure detection such as pressure transducers that may be used in a cockpit indicating system. There are, however, additional criteria that apply to cockpit indicating systems which are very important.

The contract statement of work which established the requirements for this report stated that "TPI systems shall be designed so that failure of the TPI system shall not compromise the safety of a parent system nor result in false pressure indications which would require a scheduled flight to be aborted."

This obviously would appear to be a valuable design criteria since false warnings that cause an aborted takeoff can be costly and hazardous. A system that is designed to reduce hazards by providing an early warning of an impending tire problem should not actually increase exposure to hazardous aborts by giving false warnings.

Before this was accepted as an absolute design criteria, the situation was discussed with pilots and airline personnel involved in the selection of such a system. Virtually 100% of the pilots and potential airline users contacted (approximately 30 individuals total) listed as their most important concern about a cockpit indicating TPI system was that it give reliable and accurate indications free from false warnings. In most cases, this was vehemently expressed.

Therefore, the main design criteria by which all systems are judged in this report, is their ability to operate 100% free from false warnings. In other words a cockpit indicating system shall be able to always differentiate between an actual low pressure tire and a tire that merely appears to be low through a system fault. The reliability analysis and the tradeoff study in this report will comment further on the ability of the systems to meet this criteria.

The second design criteria, and only slightly less important, is that the TPI system should be capable of detecting its own passive failures that would cause it to fail to properly indicate a low tire. The estimated ability of each system to meet this criteria is also discussed in the Reliability section.

Although, it may be argued that the high reliability of a particular design or the short exposure period on takeoff roll makes the probability of false or passive failures

remote still it is believed that approaching the design from the viewpoint of allowing no false warning and undetected passive failures will ultimately produce a system that most closely meets this objective. Further, it is not believed that the imposition of this criteria would unfairly eliminate less expensive or simpler approaches to TPI. All serious proposals for aircraft systems have been included in this study with comments made on the ability of the various systems to meet this criteria.

a. Direct Pressure Sensing Concepts

1. Analog tire pressure detection

Concept D - Tire Condition Sensor (Analog Pressure Indication - Cockpit)

The first concept in the category of systems which detect actual tire pressure is based on two building blocks:

- o Pressure Transducers Which Pick Up Tire Data
- o A Microprocessor Which Controls, Processes and Displays This Data

The transducers receive power and transmit their signals back through an inductive coupling - concentric coils - to the processing and display unit. This unit contains the microprocesser which controls the display to the crew.

A pre-determined, inflexible hi-lo limit can be set so that all tire pressures are checked to see if they exceed these limits and a go/no-go message could be displayed to the crew. While this method is simple and straight forward, it has some drawbacks. It ignores temperature entirely, which has an influence on pressure.

One way of taking temperature into consideration, although indirectly, is to take all tire pressures, average them and compare each tire and see if they all fall in a predetermined band around this average. If any tire or tires fall outside the band and/or if any tire is outside of the absolute hi and low, a warning would be displayed to the crew.

Besides being able to identify system failures the system can also be programmed so that upon command it would identify each tire with the actual numerical value of the pressure in that tire. This, coupled with a remote controller plugged in

at a connect point in a wheel well can aid ground service personnel in tire pressure inspection and maintenance. This remote controller could include a printer that would furnish a hard copy of the tire pressures for record keeping.

The system can be programmed to check all tires and automatically stop or automatically scan all tires over and over until manually stopped.

Since the system is very flexible, a number of display configurations and modes are possible.

For the cycle and stop mode, the display could range from simple warning lights to alphanumeric indicators pinpointing mis-inflated tires, actual pressures and so on. The latter might look like Figure 5. When the read button is pressed, the system display would show "88" to test all display light segments. Shortly after it would display "GO" if all tires were properly inflated. If a low tire was detected the display would show the tire number. If there is more than one mis-serviced tire, every time the read button is pressed, the next bad tire number would be displayed.

When all tires have been checked, the end of check message "EE" would show and the system could be turned off by pressing the read button one last time. If all tires are good the display would show "GO."

The system has a self check capability and will warn the operator of two kinds of failure.

1. System failure. An "FF" will be displayed after "88" when read button is pressed. This will indicate a malfunction in the computer rendering the whole system inoperative.

2. Wheel component failure. An "F" plus the wheel number will be displayed. For example, "F13" indicating that no information can be obtained from tire No. 13 due to a component malfunction in that particular wheel.

Concept D has been developed and bench tested. Aircraft testing is planned but at this point not yet accomplished.

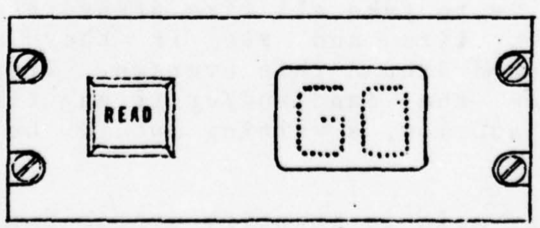


FIGURE 5. PROPOSED COCKPIT SYSTEM DISPLAY INDICATOR (CONCEPT D)

Concept E - Tire Pressure Indicating system (Analog Pressure - Cockpit)

The second direct tire pressure reading system is designed to measure and display the tire inflation pressure and/or any measurable wheel or tire parameter. These parameters may be measured and displayed whether the wheel is rotating or stationary.

The system is comprised of five elements: (Figure 6)

1. Miniature Pressure Transducer	1 per wheel
2. Data Package	1 per wheel
3. Rotating Magnetic Slip Ring	1 per wheel
4. Data Reduction and Multiplex Unit	1 per aircraft
5. Cockpit Display Unit	1 per aircraft

The pressure transducer mounted in the tire inflation valve assembly, or overfill valve assembly, senses the inflation pressure, producing a 6-bit binary word once every 100 msec. This permits measurement of the pressure to the nearest 2 psi or better, assuming a maximum pressure of 250 psi.

At the data reduction unit, the individual tire inflation pressures can be compared to other tire measured pressures, as well as compared to pressures stored in preprogrammed memory.

One of the areas of concern is presenting a false pressure reading which would result in an unwarranted and costly abort or turnaround. This can be minimized as follows:

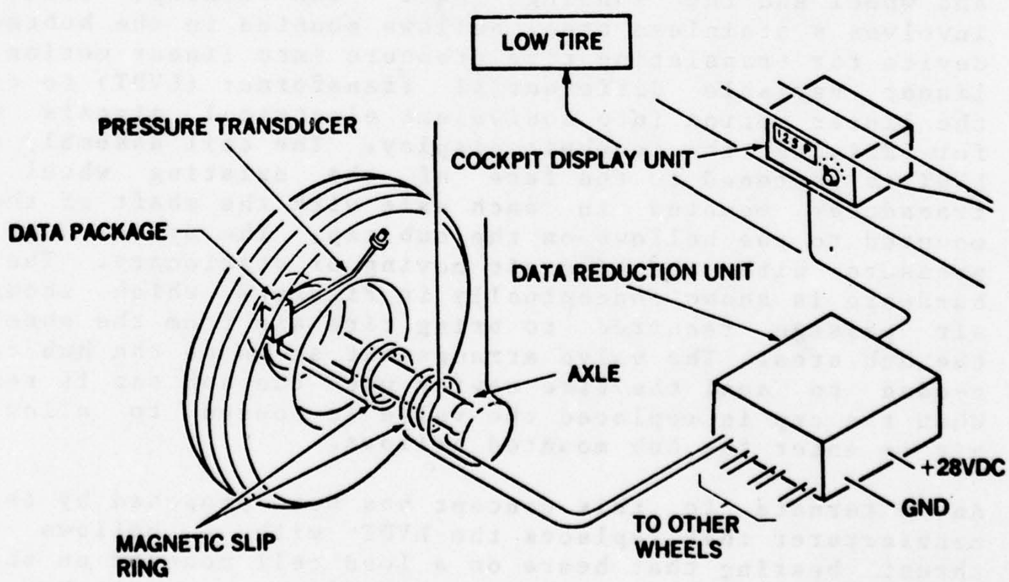


FIGURE 6. ACTUAL TIRE PRESSURE INDICATING SYSTEM (CONCEPT E)

1. Add hi-lo's plus parity bits to the basic [illegible]-bit word. These bits would verify the integrity of the system, including the pressure transducer, since extreme bridge unbalance (due to opens or shorts) would add extreme readings and failure of the A-D (Analog to Ditigal converter) would negate the parity bits.

2. Secondly, comparison between adjacent and other aircraft wheels would permit flight engineer's analysis based on pressure and temperature. Thus, false data due to system malfunction can be easily determined.

A typical hubcap axle - mounted magnetic slip ring unit is shown in Figure 7. This design is based on mounting the coaxial transformer at the anti-skid transducer drive interface. In this case, the rotating coil is assembled to the bellows drive; and the nonrotating coil is assembled and concentrically registered to the anti-skid transducer.

This system is in the conceptual stage of development with only the transformer/coupler actually bench tested.

<u>Concept F - Linear Variable Differential Transformer (LVDT) System (Analog Pressure - Cockpit)</u>

This system provides a direct linear readout of aircraft tire pressure. Once the tire pressure signal is obtained, it is transferred across the interface between the rotating tire and wheel and the landing gear. The concept recommended involves a stainless steel bellows mounted in the hubcap as a device for translating tire pressure into linear motion and a linear variable differential transformer (LVDT) to convert the linear motion into equivalent electrical signals usable for driving the cockpit display. The coil assembly of the LVDT is fastened to the face of the existing wheel speed transducer mounted in each axle with the shaft of the LVDT mounted to the bellows on the hub cap. The system can read pressure with the aircraft moving or stationary. The wheel hardware is shown conceptually in Figure 8 which shows the air passage required to bring tire air from the wheel into the hub area. The valve arrangement shown on the hub cap is needed to seal the tire cavity when the hub cap is removed. When the cap is replaced the valve is opened to allow tire air to enter the hub mounted bellows.

An alternate to this concept has been proposed by the same manufacturer that replaces the LVDT with a bellows driven thrust bearing that bears on a load cell mounted on the face of the anti-skid transducer. Both of these approaches are in

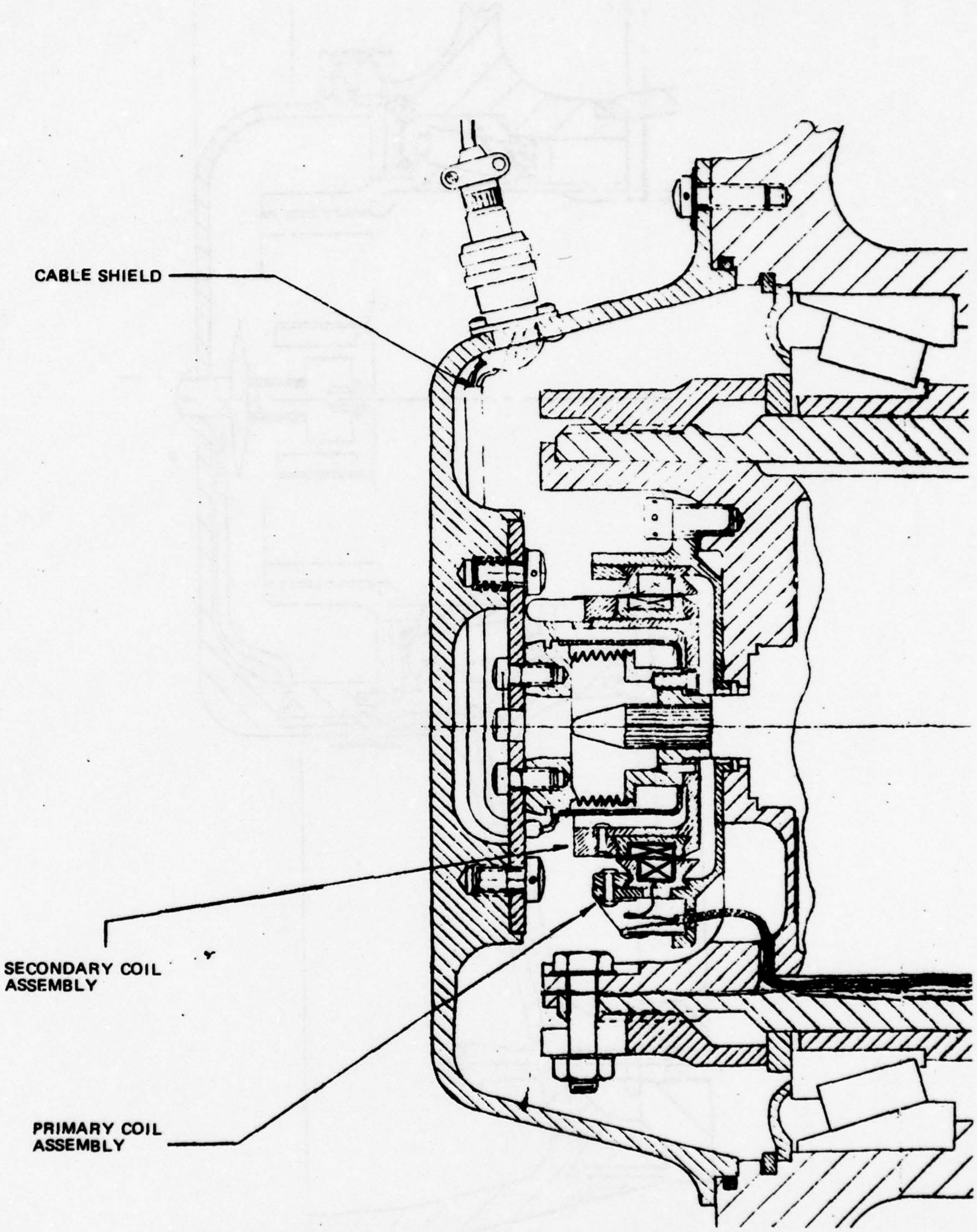


FIGURE 7. TYPICAL MAGNETIC SLIP RING INSTALLATION (CONCEPT D AND CONCEPT E)

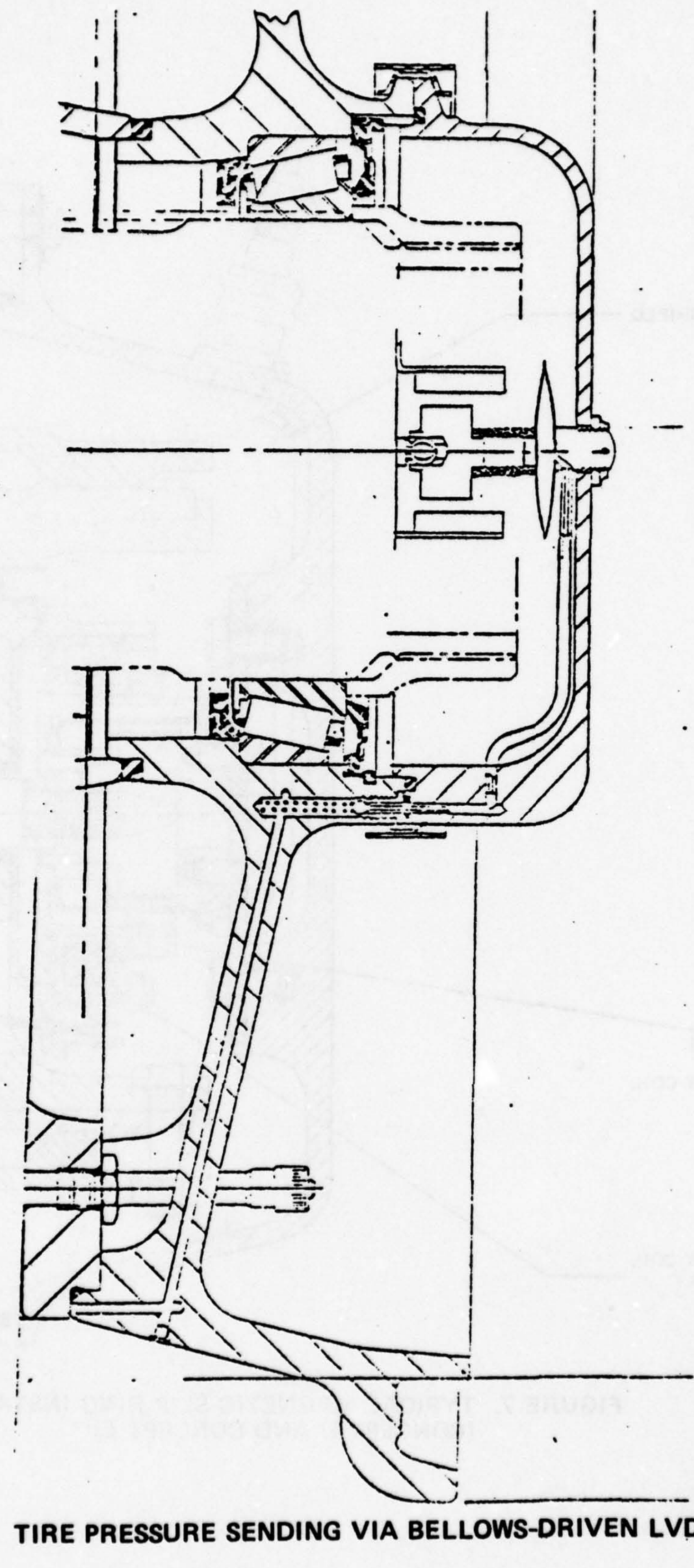


FIGURE 8. TIRE PRESSURE SENDING VIA BELLOWS-DRIVEN LVDT (CONCEPT F)

the conceptual stage of development. This concept could also be applied to aircraft not fitted with an antiskid system but all the study aircraft do have antiskid systems.

Concept G - Tire Pressure Indicating System via Slip Rings (Analog Pressure - Cockpit)

The system designed for large commercial aircraft, consists of tire pressure transducers, a wheel/axle positive contact signal coupler, a microprocessor controlled computer, and a display panel output. The axle coupler provides a method for positive and direct transferal of signal data from the transducer to the TPI computer. This is accomplished through a special slip ring assembly. The TPI computer will be housed in a standard ATR short box which will be environmentally sealed.

A "tire pressure low" warning will occur whenever two adjacent tire pressures differ by approximately 20% or whenever any tire falls below a predetermined fixed minimum warning threshold. The computer will incorporate a failsafe system to detect component failure, inconsistent results, or other types of system malfunctions. The overall system accuracy with respect to warning thresholds is estimated to be $\pm 5\%$.

Selection of the proper microprocessor allows minimum hardware and minimum interconnects for reliability. In addition, all input and output lines from the computer will be optically isolated from the environment so that transients or noise from the environment cannot affect the accuracy or reliability of the system.

2. Binary or Discrete Pressure Sensing System (Discrete Pressure - Cockpit)

Concept H - Tire Deflation Warning System

This system is intended to monitor the tire pressure of an aircraft, to detect if this pressure has decreased below a dangerous value that threatens tire integrity. This detection is performed by pressure switches mounted on the wheel rims and which are in motion with them while the aircraft is taxiing. The data transmission between the wheels in motion and the fixed part of the landing gear is made by electro-magnetic induction. The signals are treated electronically and the warning signals are displayed on the instrument panel. A transmitter-receiver circuit observes the magnetic state of the pressure switch circuit while the aircraft is taxiing. A data processing unit processes the response signals delivered from the wheels and sends a warning signal to the cockpit when a deflation is detected. The aircraft is required to travel at a speed of at least 3 knots before a correct warning signal is obtained. Then the system is inhibited when the taxi speed is less than 3 knots and more than 80 knots, and when the aircraft is airborne. Accuracy of the switching pressure is ±5% of the pressure.

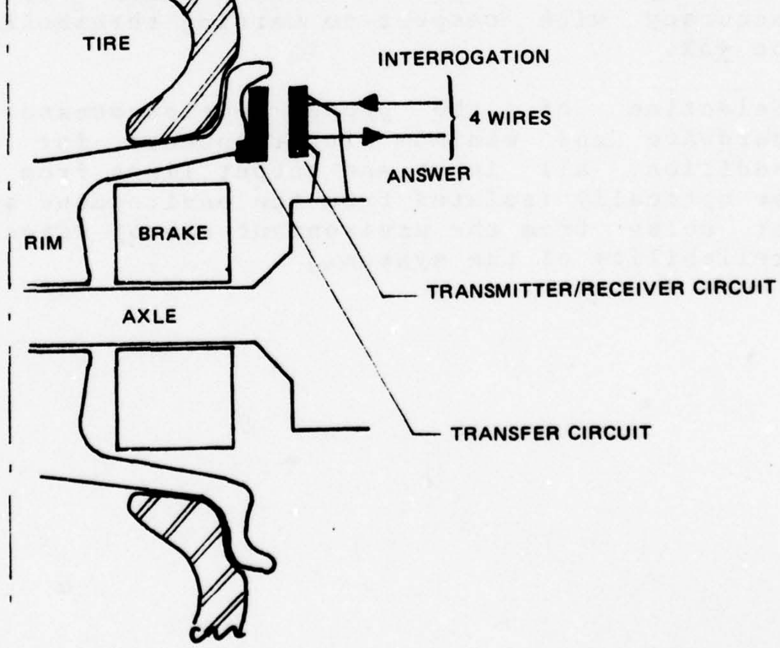


FIGURE 9. WHEEL MOUNTING CONFIGURATION (CONCEPT H)

The unit sensitive to the pressure is a pressure switch type piston-spring. When the tire pressure is above the warning pressure, the spring is compressed, and an electrical contact is established between the piston and a set screw. When the pressure in the tire drops to the warning pressure, the contact of the pressure switch opens.

The transmitter-receiver circuit observes the magnetic state of the pressure switch when the aircraft is taxiing. These two circuits are opposite each other. Thus 4 wires are required from each stationary wheel circuit to the computer. The spacing between the coupler is about 10 mm.

When a wheel is deflated, the data processing unit does not receive any signals from the corresponding channel, and sends a warning signal to the cockpit with a 3 second delay. A diagram of the coil installation is shown in Figure 9.

<u>Concept I - Differential Valve Discrete TPI System (Discrete Pressure - Cockpit)</u>

A system which could be adapted to any aircraft wheel configuration is designed for sensing low tire pressure on any aircraft. It utilizes the differential valve as the "brains" and the remaining tire pressure for the "muscle" to activate a warning signal.

The following numbers being each denoted a specific area on Figure 10 will give a better understanding of the system.

1. Tire Pressure Sensing Port.

2. Differential Valve #1 - - replaces the normal service valve and is calibrated to activate when routine service is required.

3. Indicating service valve cap - - bright yellow pin (when visible) indicates air should be added for optimum tire pressure.

4. Differential valve #2 - - calibrated to activate when corrective action by flight crew should be initiated.

5. Air Passage - - Pressurized only when differential valve #2 is activated.

6. Stainless Steel Bellows - - Extended when differential valve #2 is activated.

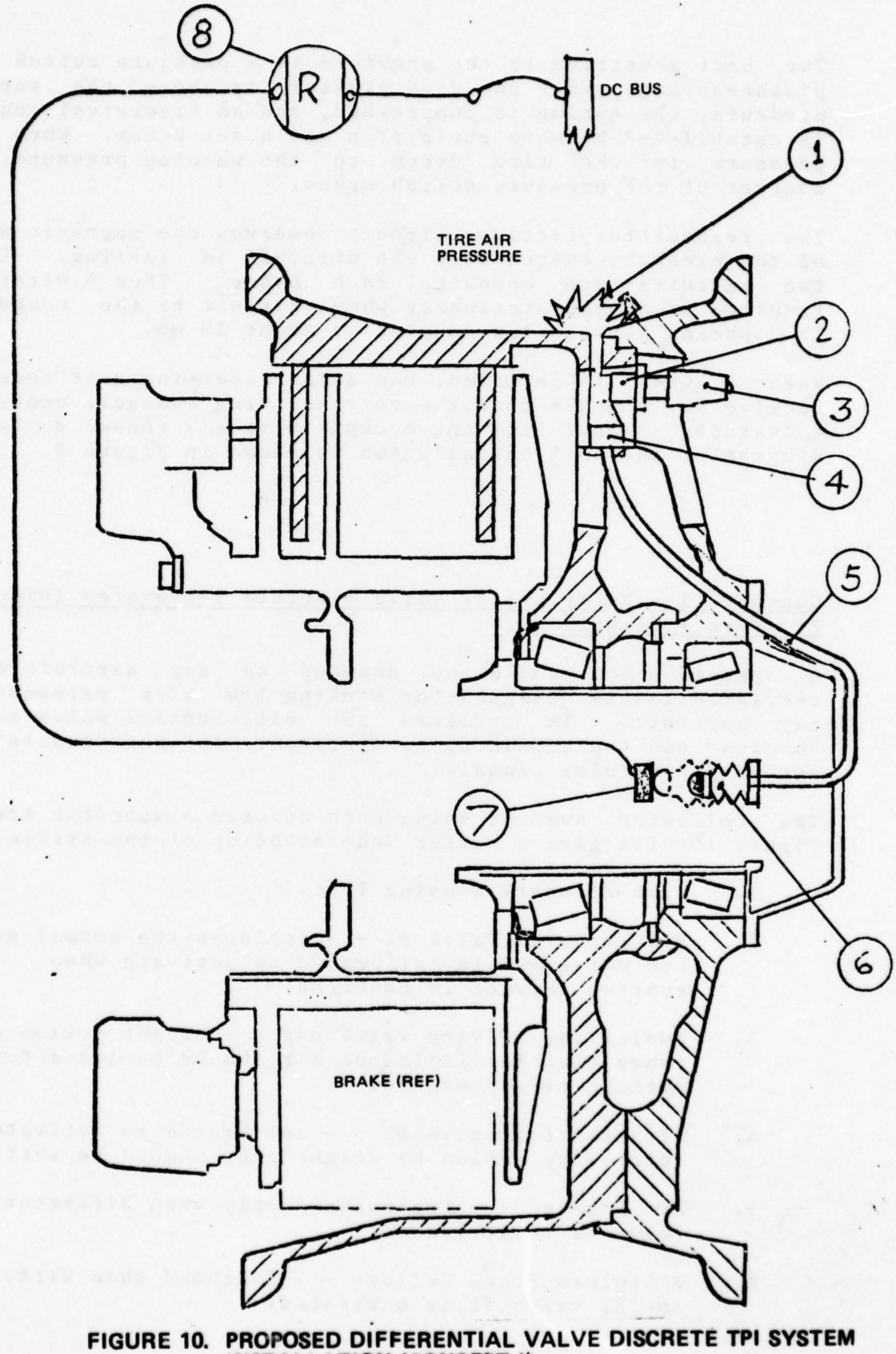


FIGURE 10. PROPOSED DIFFERENTIAL VALVE DISCRETE TPI SYSTEM INSTALLATION (CONCEPT I)

7. Fixed Contact - - Communication with extended bellows (6)rovides electrical ground path for flight station indicator.

8. Flight Station Indicator.

A further refinement of this system combines the two differential valves into one and adds a pressure transducer in passage #5. This transducer is connected only when the bellows is extended making slip ring contact across the air gap. Thus the slip rings do not have to be in continuous contact for wear and for the short time they are in contact, contact forces can be high. The transducer can then be used as a reasonableness check to protect against false warning due to a failure of the differential valve.

Concept J - Discrete TPI System (Direct Pressure - Cockpit)

The system, similar to concept E, has been developed for highway vehicles. It consists of the following components.

1. Pressure Switches at the Tire Fill Valves.

2. Coupling Coils (Rotating in Conjunction with Wheels).

3. Transmitter/Receiver Coils.

4. Al Electric Control Unit.

5. A Warning Unit (Indicates Failures Optically and/or Aurally).

The system requires the vehicle to be in motion to function. The first automatic check-out of the system is the functional check of one wheel circuit counter, output signal amplifier and warning unit. If no component failure is detected the warning unit will indicate a "false failure" which will be cancelled after the first wheel revolution is completed. The system is at fault if no false warning is indicated prior to the start of wheel rotation.

While the aircraft is rolling the tire pressure in each individual wheel is continuously monitored at periodic intervals. In order to accomplish this task, the electronic control unit delivers an AC output signal, which is constantly present at the transmitter coil of each wheel. As soon as the coupling coil - which is attached to each wheel and which is part of an independent electrical circuit

together with the pressure switch - is in a position exactly the opposite to the transmitter coil, an inductive AC signal is fed back through this circuit to the electronic control unit via the receiving coil. (See Figure 11).

This however is true only as long as the tire pressure is above nominal pressure, thus keeping the pressure switch contact closed and the coupling circuit uninterrupted.

In case of low tire pressure - with an open pressure switch and interrupted coupling circuit - there will be no return signal to the electronic control unit. The unit will detect the abnormal condition and immediately provide a warning to the operator.

The above mentioned check-out of each individual tire pressure is constantly accomplished by the electronic control unit in a predetermined sequence as long as each individual tire pressure is above nominal.

In order to increase the system reliability, the electronic control unit receives the return signals from the wheels via two separate channels for double-checking purposes.

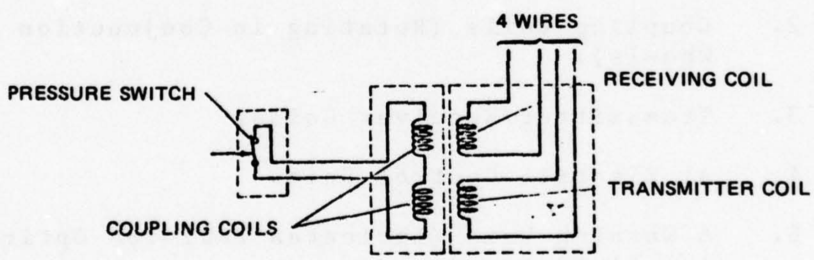


FIGURE 11. COUPLING COIL CIRCUIT (CONCEPT J)

Concept K - Discrete TPI System Via Hub Mounted Switches (Direct Pressure - Cockpit)

This system is a low tire pressure warning system designed to warn the driver of a highway vehicle underinflated tire, loose rim, wheel or a hot bearing.

The system consists of a sensitive pressure detecting system installed on the hub of each wheel. This system connects to the valve stems of both tires (adapts to a single tire when not used on duals). The system is preset for desired warning pressure with a flashing warning light. When any tire connected to the system falls below the preset warning pressure the flashing light is instantly activated.

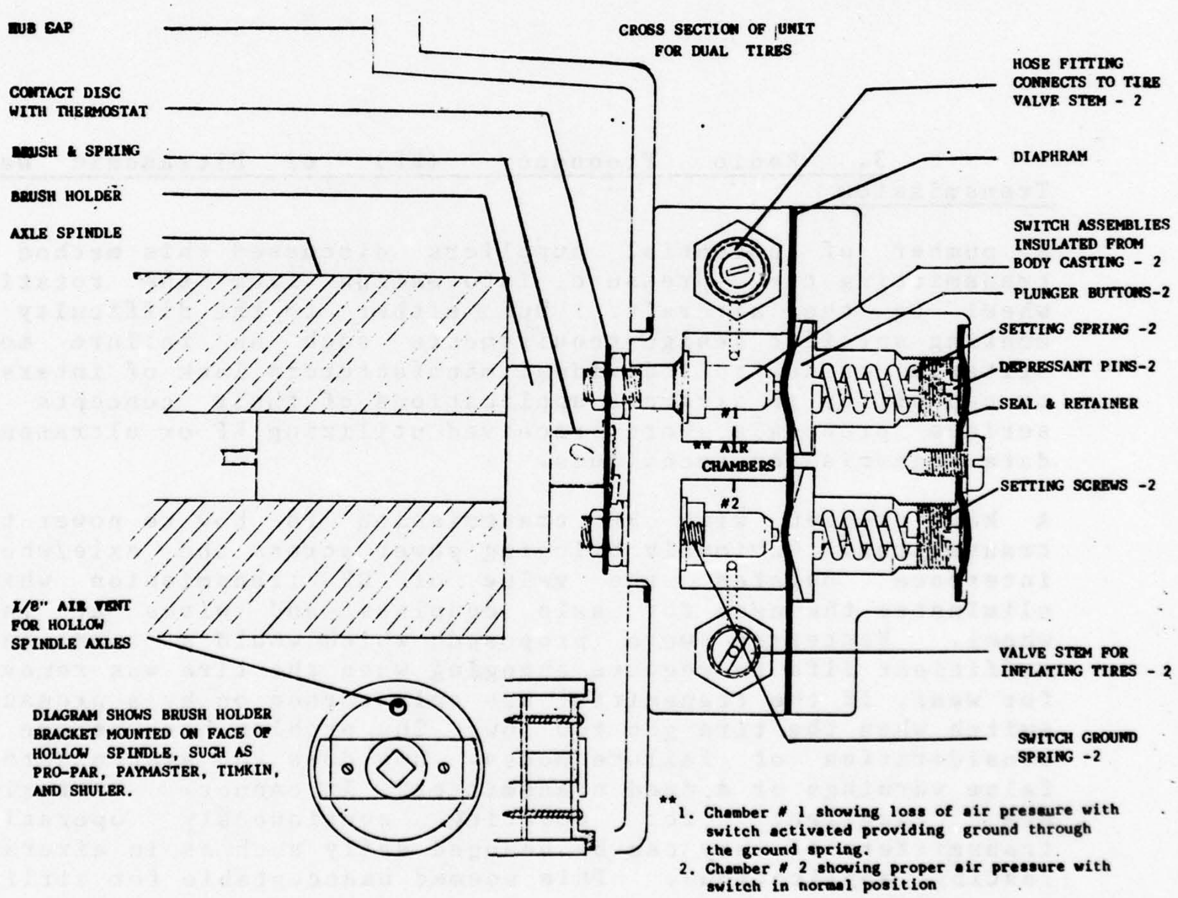


FIGURE 12. HUB-MOUNTED SWITCH INSTALLATION (CONCEPT K)

The system is equipped with thermostats to detect hot bearings.

An inflating hose attached to the air brake reservoir provides a simple tire inflating method on the road eliminating the changing of tires between terminals (truck installation).

The push buttons on the unit serve a dual purpose.

a. For Testing the System.

b. For Testing Individual Tire Pressure.

Multiple warning lights can be installed to pin-point malfunctioning of tire or bearing.

The hub mounted switches are shown in Fig. 12.

3. Radio Frequency (RF) or Ultrasonic Data Transmission

A number of potential suppliers discussed this method of transmitting tire pressure information from the rotating wheel to the aircraft. Due either to the difficulty in meeting specific design requirements such as failure mode criteria or due to individual manufacturers lack of interest or capability in aircraft applications of their concepts no serious proposals were received utilizing RF or ultrasonic data transmission techniques.

A key problem with RF transmission is how to power the transmitter. Obviously bringing power across the axle/wheel interface negates the value of RF transmission which eliminates the need for axle couplers and wires at each wheel. Batteries were proposed which would at least have sufficient life to require changing when the tire was removed for wear, if the transmitter was only turned on by a pressure switch when the tire got too low. The problem here became a consideration of failure modes. How does the system detect false warnings or a dead transmitter? It cannot. Batteries are excellent for powering continuously operating transmitters if they can be changed daily such as in aircraft testing applications. This seemed unacceptable for airline operation.

Other methods of powering transmitters were proposed such as a generator built into the wheel hub or a pogo stick type device mounted inside the tire that would provide a small

amount of power when deflected at the bottom of each tire revolution. These approaches were not seriously proposed as it appeared the installation simplicity of the RF system was being outweighed by added complexity of the transmitter powering device. Further to get around the problem of failure modes due to failures in the transmitter discrete keying method multiple (one for each tire) transmitters continuously in contact with the same number of receivers began to appear to be too complex.

The ultrasonic method is a proprietary concept that allowed a small amount of tire air to be used to blow an ultrasonic whistle when tire pressure dropped below a certain point. Failure modes such as a failure to actuate when a tire was actually low, an actuation when the tire was not low, a failure to turn off the whistle once started causing complete tire deflation, the possible need to add an accumulator with enough air to blow the whistle when the tire failed explosively and other considerations caused the manufacturer to withdraw this proposal.

b. Indirect Low Tire Pressure Sensing.

Concept L - Weight and Balance Low Tire Indication (Indirect Indication - Cockpit)

The weight and balance system (WBS) presently in service on one wide body aircraft can be utilized to sense a blown or low pressure tire on the main landing gear. Additional wiring from main landing gear junction boxes to the lower electronics bay area would be required. A 1/4 short ATR box located in the lower electronics bay would be required to house tire indication circuitry. Indication of a blown tire is provided to the master caution warning panel by a contact closure to ground to drive a single light. The warning light is duplicated on a control panel at the flight engineers station. Two additional lights to isolate the tire failure to one of the main landing gears are also provided at this location along with test, reset, and power pushbutton switches.

System Description

Main landing gear. The weight and balance system (WBS) transducers measure the shear deflection of the bogie beam or axle between each tire and the vertical strut. Under normal operating conditions each main gear tire reacts an approximately equal amount of force but there are relatively small differences between tires. The small differences caused by uneven terrain, friction in pitch pin, braking, and roll moments are averaged out by installing four transducers on the main gear, one for each tire. A blown tire will cause the forces to redistribute drastically such that the force on the blown tire becomes zero or nearly so, the force on the directly opposite tire is doubled, the forces on the other two tires remain approximately the same. This large difference in forces allows a blown tire to be sensed with ease if the proper circuitry is provided.

As the system is now configured the four transducers are wired in parallel at the landing gear. The resultant output to WBS computer is the average vertical force on the gear. Braking forces are cancelled by the forward and aft pair of transducers. Torsional forces are cancelled by the inboard and outboard transducers of a pair. A blown or low tire indication must be sensed by comparing the individual outputs then be recombined to provide the extraneous force cancellations mentioned above.

System Interconnection

The four transducer signal pairs from each main gear must be routed to the blown tire indication unit.

After the first tire blows out the second tire expected to blow would be the one just opposite which would be carrying twice the normal weight. If the transducer associated with these two tires were connected as a pair, the first blown tire would cause an indication. If the second tire blows the forces redistribute back to normal. The reset button could be depressed and the blown tire indication could be falsely deleted. To preclude this the diagonal transducers are connected as a pair.

Nose Gear Center Switch

An output from the electronics unit is provided so that when the nose gear is not centered the electronics unit will be deactivated. This is done to insure that there will be no false indication when the aircraft is turning.

Indicator Unit

Two indicator lights, L. Main and R. Main are all driven from the electronics unit by latching relays. After a blown tire is indicated the relays remain latched, even if power is temporarily interrupted, until the reset button is depressed. If the blown tire has not been replaced and the aircraft is not airborne the blown tire indication will return after the reset button is released. While airborne depressing the reset button would reset the relays to their initial condition and the blown tire indication circuits would not be activated again until approximately 75% of the basic or empty weight was again carried by the main landing gear.

The test button is provided to allow a confidence check of the tire indication system. Depressing the test button inserts signals at the input of the signal conditioning circuits that simulate blown tires on the two inboard tires of the right main gear, and the two inboard tires of the left main gear. If the electronic circuits associated with each of these tires is operating properly the two individual gear lights will be lighted. The test circuit will operate either while airborne or while on the ground. This test circuit tests 85% of the components of the system. An additional test button, now provided only on the electronics unit would be required to increase the component test percentage to 94%.

Concept M - Weight And Balance - Blown Tire Indicator (Indirect Indication - Cockpit)

The concept M Blown Tire Indicating system was designed to warn the crew that they had a blown tire or deflated strut on the B-747. The design of the system takes advantage of the existing weight & balance equipment already on the aircraft. The sensing technique operates on the theory that if a tire should blow, the transducer output related to that wire would decrease. With proper summing and comparing transducer outputs alarm conditions can be detected. This technique can also be used to detect a deflated strut.

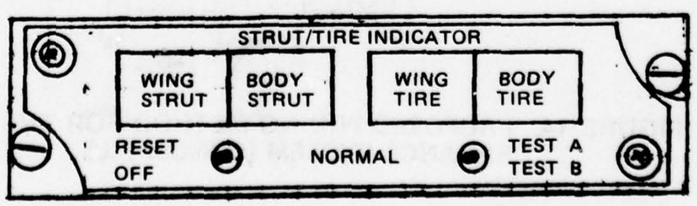


FIGURE 13. STRUT/TIRE INDICATOR (CONCEPT M)

The system consists of two basic components: the channel comparator, and the strut/ tire indicator (Fig. 13). In addition to existing weight and balance components. The function of the tire alarm system, is to receive signals from the weight & balance aids output and to provide an alarm when the difference in any pair of complementary channel signals is greater than a predetermined level. Two alarm levels are provided, one for static operation, which will allow closer tolerance alarm levels, this level is used when the aircraft is at rest. The second level is used for dynamic operations. It has a wider alarm band to allow for the greater variations encountered when the aircraft is rolling.

In order to accomplish this, transducer outputs in the weight & balance system have been rewired. The most desirable wiring method is shown in Fig. 14. If a tire for example #3, should deflate then the transducer output related to that tire would decrease and then, because of the bogie design, the transducer output from 3′ would also decrease, while the outputs from 4 and 4′ would increase. The resulting difference in outputs between channels 3 and 4 would be greater than the normal operating difference, allowing electronic comparator circuits to sense this difference and produce an alarm. Similarly, if strut W1 was deflated, outputs 3 and 4 would be lower than outputs 5 and 6, resulting in a strut alarm condition. The system at present can detect a blown tire or deflated strut in either wing or body without distinguishing between the left or right side of the aircraft.

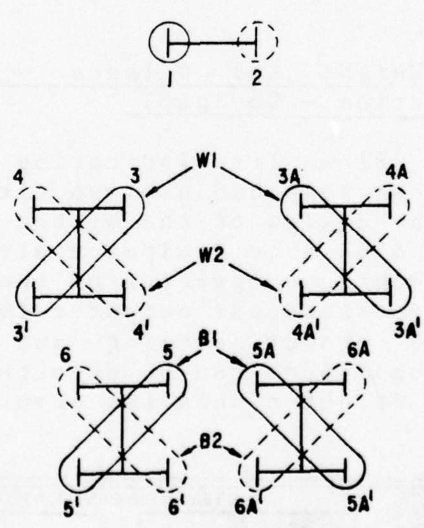


FIGURE 14. PROPOSED WIRING METHOD FOR THE WEIGHT AND BALANCE SYSTEM (CONCEPT L)

The strut/tire indicator is housed in a separate case that will mount in the standard panel mount on the engineer's panel. This panel contains lights that will advise the crew of the location of a blown tire or deflated strut along with a RESET OFF and TEST switch. The RESET OFF switch is used to disable the alarm in the event of an operational false alarm conditions, such as might be created during a tight turn. The OFF position (maintained OFF) side of a switch breaks the continuity of the +28V energizing relays and indicator lights. This would also reset the alarm circuit. A latching type alarm was incorporated in order to sense two or more blown tires, providing that they do not occur simultaneously but sequentially, separated by two to five seconds minimum. The alarm will see the first blown tire, latch and remain latched until the alarm condition is eliminated and the RESET switch pushed.

The TEST switch is used to compare the signals of the individual bogie or gear to determine if the alarm system is functioning properly. This approach was taken to avoid possible errors caused by lateral unbalance in a loaded aircraft. All alarm lights will come on when either of the momentary TEST switches are pushed. This alarm can be reset by using the reset switch. Both momentary switches should be in the normal position under standard operating conditions.

<u>Concept N - Wheel Speed Sensing (Cockpit Indicating)</u>

One manufacturer has proposed a wheel and brake advisory system which among other antiskid system and brake system monitoring functions is designed to detect underinflated tires when the aircraft is rolling. The system uses existing antiskid system transducers for wheel speed information and is claimed to be able to reliably detect tires that are over 50% under inflated. The system was originally developed for the DC-8 and has been service tested in a version that did not offer the underinflation detection feature. A later version of the system with the underinflation/flat tire detection feature developed for the B-727 has been tested outside of normal revenue service.

The system intended for installation on board a B-727 type aircraft was designed to detect and indicate the following condition of the tires, wheels, and brakes.

a. Tires
   -- Underinflated and blown tires

b. Wheels

-- Bearing breakdown, etc.

c. Brakes
-- Overheated bound brakes at taxi out.
-- Binding or draggy brakes after take-off.

Inboard and outboard wheels will be compared for a and b, individual wheels will be compared for condition c.

The system will operate from the present anti-skid wheel speed transducers, without affecting the anti-skid system in any manner whether the anti-skid system is on or off. It consists basically of a control box, 3/8 ATR short, and suitable annunciation indicators.

By utilizing the presently installed wheel speed transducers a minimum amount of additional wiring will be required. Additional wiring to the cockpit is minimal and might consist of one indicator and power control. Individual indication of malfunction can be indicated at the control box.

The present anti-skid test will also check the wheels and brake advisory system.

The system detection set points for all phases of operation may be readily changed, for instance, in the ground mode, wheel difference comparison detection threshold and the time duration of speed difference. This allows the system to be readily adaptable to various types of aircraft and various conditions without minor changes.

The system may be inhibited in the ground mode at any particular speed (60 knots) where operation of the system may not be required.

The system can be inhibited via nose wheel steering to prevent wheel speed differences while turning the aircraft to cause false malfunction indication.

The system may also be inhibited in the ground mode operation for aircraft attitude or tilt caused by a crosswind.

In the airborne mode at lift-off the system by means of nose wheel relay logic changes the system detection to individual wheel deceleration rate time and indicates a binding brake if one should occur until gear-up logic inhibits the system. This method of detecting a binding brake is more reliable and realistic than comparing paired wheel deceleration, i.e. 2 wheels could conceivably have binding brakes and comparing them to each other would not indicate that either brake was decelerating the wheel too soon.

A binding brake then occuring after lift-off and before gear-up command, would give an indication, latch up the indication system and continue to indicate a malfunction until manually reset.

The system is offered with the underinflation detection feature only. The manufacturer claims that a 50% underinflation condition was stably detected by the system during taxi tests at 15 knots on a 727. A 25% underinflation should be detectable at 30 knots with corresponding higher sensitivities at slightly higher speeds.

Concept O - Low and Failed Tire Detection/Indicating System (Indirect Indication - Cockpit)

Information from a new strain gage based weight and balance system manufacturer received late in the report study is included although the concept has not been analyzed as part of this report. It is based on comparing the signals from the WBS (Weight and Balance System) load deflection transducers mounted in a four-way arrangement on each bogie beam. The system can detect tire differential pressure conditions with either bogie-mounted or axle-mounted transducers, for either two-wheel or four-wheel gear. The differences between transducer signals (indicated loads) for each pair of wheels are chiefly proportional to the tire pressure differences. A differential tire pressure of 5% can be reliably detected under static conditions and that a differential pressure of 20% can be detected under the dynamic conditions of the take-off or landing roll. The system consists of landing gear mounted deflection sensing transducers, remotely located multiplexers which obtain individual transducer signal information, a computer and a control and display unit. There are no structural modifications required for the transducer installation on most present wide-body aircraft.

The manufacturer has also proposed that the tire structural or tread anomalies are detectable by dynamic analysis of the weight transducer signal and tire rotation information. With appropriate digital signal processing techniques, tire defects can be detected even in the presence of runway/taxiway roughness, braking, and other operational factors. Such a system may provide early warning of thrown treads or tread conditions that will soon cause loss of the cap.

III ANALYSIS OF SYSTEM DESIGN FEATURES AND COMPARISONS

A. WHEEL MOUNTED GAUGES AND DEVICES

Concept A and B gauges are well suited to the intended application. They provide a quick and easy way for maintenance personnel and flight crews to check tire pressure. By facilitating tire checks the gauges should allow underinflated tire to be caught before the carcass is damaged or before the tire fails. There should be benefits in terms of reduced maintenance time (see Maintainability section) and possibly reduced tire failure rates due to the increased frequency of tire checks.

A buyer may choose between the two gauges based on their own preference for dial design or the particular manufacturer. The design and performance of the gauges should be equivalent. The buyer further can choose to buy gauges with color banding or with plain faces. Color banding requires different gauges to be purchased and stocked for different wheels and tires for a particular aircraft or airline fleet. It has the disadvantage of increased cost and the risk of installing the wrong gauge on a wheel. Color banding has the advantage of improved readability and eliminates the need for maintenance crews or flight crews to refer to tire inflation charts.

No colorbanded or plain dial faces allows one gauge to be installed perhaps on an entire airline's fleet thus reducing spares and stocking costs. This gauge does however, require that some reference be made to tire inflation charts. These charts are readily available to maintenance crews but may not be so readily available to flight crews.

One complaint leveled at the gauges has been that their readability particularly at night and during inclement wet or snowy weather is impaired particularly if the gauge is upside down at the bottom of the wheel. All considered, however, wheel mounted gauges appear to be a significant advance in aiding good tire maintenance.

Concept C pressure switches with handheld interrogator approach to tire maintenance may also find acceptance. With this approach separate fill valve switches are required for each wheel type (different pressure) as with colorbanded gauges. The hand held interrogator provides a very readable go-no-go indication day or night and should eliminate the need for a flashlight that is probably required to read gauges at night.

When considering the added cost of the hand held interrogator, problems of storing the interrogator and maintaining the interrogator the wheel mounted gauge has some

advantages. Also an analysis should be made of interrogator and switch failure modes to determine if there are failures which cause the interrogator to fail to detect a low tire. Also to maintain accurate indication of a tire that is 10 to 15 psi underinflated the pressure switch must (as it is) be temperature compensated. The problem with temperature compensation is that it will mask a tire that has become underinflated due to the cooling of the tire air mass when an airplane lands and perhaps overnights in a cold climate. (This will be discussed further in a later section).

B. COCKPIT INDICATION VS. GROUND READOUT GAUGES

What are the relative advantages of ground readout devices vs. cockpit indicating systems? Obviously cockpit systems are going to be significantly more expensive to install and maintain. Can they be cost or safety justified?

In general, cockpit indicating systems that provide accurate on aircraft readout of tire pressures, whether in the cockpit or in another readily accessible location, once accepted as sufficiently reliable, can provide the optimum ease in checking tire pressures. Problems of weather that may discourage checking wheel mounted gauges and eliminating problems of reading gauges at night are all pluses for on-board readout systems. The Concept D system even proposed a hard copy printout of tire pressures for the aircraft log. (This may require a hand held separate printer which could be objectionable). As is shown in the maintenance section this relative ease of use shows the on-board analog readout system can provide an additional small cost saving in tire maintenance time.

Based on the above analysis ground readout gauges offer a major improvement at lower cost. The major area of difference, however, is in the ability of the cockpit indicating system to warn the flight crew of a tire problem that develops after push back, on taxi-out and takeoff roll. From the analysis of damage costs and incidents and accidents in appendix A, a case is developed that cockpit indicating systems may be cost justifiable (except for some study aircraft) due to reduced serious tire related rejected takeoff incidents and attendant increased safety.

From this it may be concluded that the most simple go-no-go system could be most cost justified, wheel mounted gauges could provide quick pressure checks at the dock and a simple go-no-go system could provide warning of a problem developing after pushback. However, when considering failure modes and the requirement to reduce false warnings on takeoff roll to a minimum, an analog system, whether or not actual pressure is cockpit displayed, has certain advantages beyond the ease of tire pressure readout.

C. DESIGN CRITERIA/CONFORMANCE WITH FAR 25 - COCKPIT INDICATING SYSTEMS

In reviewing the requirements of FAR part 25 as applicable to cockpit TPI systems several items were found, in addition to the general requirements for proper power and light, that apply to failure criteria. These paragraphs are:

> 25.1309 EQUIPMENT, SYSTEMS AND INSTALLATIONS (b) The airplane systems and associated components, considered separately and in relation to other systems, must be designed so that --
>
> (1) The occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable, and ...
>
> (c) Warning information must be provided to alert the crew to unsafe system operating conditions, and to enable them to take appropriate corrective action. Systems, controls and associated monitoring and warning means must be designed to minimize crew errors which could create additional hazards.

Although, these paragraphs do not specifically prohibit false warnings that may cause a hazardous aborted takeoff they do lend support to the basic design criteria that requires reducing possible false warnings to an absolute minimum. Thus, per the discussion earlier in this study and FAR 25 requirements, the first design criteria for cockpit indicating TPI systems, should be:

- The TPI system shall be so designed from its inception that false warnings that could cause a takeoff to be aborted are eliminated.

The second criteria of somewhat lesser importance shall be:

- The TPI system shall be capable of being tested periodically to determine the capability of the system to detect a low tire when it occurs.

In meeting these criteria systems able to measure analog tire pressure (Concepts D, E, F, G) have a theoretical advantage over discrete or binary pressure sensing approaches. With analog data reasonableness checks can be performed to differentiate actual low pressure conditions from system failures. A reasonable pressure range from 0 to 350 psi might be established with pressures falling outside this band considered to be "hardover" circuit failures and not valid low pressure tires. The probability of a circuit failure that causes a false pressure indication within the reasonable range must be assessed for each of the proposed systems but through proper design should be able to be made improbable.

Unlike analog systems discrete pressure sensing systems have no means of making a reasonableness check. The ability of a pressure switch to switch when a tire loses pressure cannot be assessed before the fact. Most importantly if a switch fails and produces a false warning there is no way to check (except in Concept I), if the tire is actually low. Therefore, discrete sensing concepts H, J, and K may not be highly favored.

It may be argued that steps can be taken to minimize this effect with discrete systems. A resistor can be placed across switch contacts, for example, to eliminate open circuits in wiring to the switch from causing false warnings. Further, cutting off tire warning indications above some speed on takeoff, coupled with the relatively short time exposure to false warnings on takeoff, reduces the probability that a hazardous abort might be falsely initiated. Some have proposed two separate switch circuits on the wheel but the problem becomes which one is correct if there is a disagreement particularly when each switch will normally have a slightly different switch point.

With careful attention to circuit and switch design, the tendency of discrete systems to fail passively or produce false warnings cannot be eliminated. Passive switch failures could be detected each time a tire/wheel goes to the shop (i.e. once every several hundred landings) reducing but not eliminating the probability that the system may be unable to detect an actual low tire.

With very careful attention to design of a reliable switch and thorough testing capability of monitor circuits with monitor cutoff above 100 knots on takeoff, designs such as that proposed by Concept H manufacturer offer the best means of meeting the design criteria with a discrete pressure sensing system. If such a system offered substantial cost savings it may be justifiable. The preliminary cost estimates do not, however, appear to substantially favor discrete monitoring systems.

Analog pressure monitoring systems, weight and balance systems, and the system proposing to use antiskid wheel speed to detect underinflated tires all have analog information to evaluate (whether displayed or not). These systems are favored for failure detection ability in the main study and the reliability study included herein (done separately). The potential advantage of each of these concepts can be lost if sufficient attention is not given to the final detail design of the system to eliminate false warnings.

D. COCKPIT DISPLAYS - EVALUATION OF

In a survey of fifteen test pilots, flight engineers and airline pilots half favored the display of actual tire pressure with a "low tire" light and half favored having only a "low tire" light with some means of determining the operational status of the system. The size of the aircraft and crew workload considerations were factors in the expression of opinion.

Those favoring actual pressure display expressed a desire to know how much below the threshold pressure (i.e. specified operations pressure); a tire had fallen to give them additional data to decide whether to continue the takeoff or abort. Also, several flight engineers felt that valuable pressure trend data might be obtained for improved maintenance. Those favoring a light only indication felt having the flight engineer interpret tire pressures would require charts be provided to the flight engineer which would be a useless burden.

Several cockpit display schemes with actual pressure and/or fault codes displayed have been proposed. Selection of a specific display should be determined largely by airline preference or planned system use. Concepts D, E, F, and G could all display analog pressure or a discrete "low tire" light indication. With the same basic system and computer several different displays might be offered. Other concepts, of course, do not have the capability of displaying actual tire pressure.

In a "low tire" light only approach it has been suggested that a "system INOP" light be added that would come on automatically if the system was turned off or had failed producing a false "low tire" indication. The "low tire" light may or may not be suppressed under this condition. The idea of the "INOP" light would be to warn the crew of system failure while suppressing false low tire warnings so that a takeoff may continue uninterrupted. One airline believed, however, that whether the "low tire" light or "INOP" light were on, the crew procedure would be the same -- to return to the dock. It may, therefore, be desirable to only have the "low tire" light and to suppress false warnings until the next system self-test. Thus if tested before pushback, system faults could be verified and the system repaired or dispatched inoperative to avoid an unnecessary abort and return to dock on the prior takeoff.

Again, specific airline or airframe manufacturer's experience or their design philosophy must be taken into account when selecting a cockpit display for a particular system.

E. TEMPERATURE COMPENSATION/ACCURACY EVALUATION

Tire pressure varies according to temperature over a considerable range. This variation must be considered in the design of TPI systems. For example, pressure can change nearly ± 25% at extremes of temperature when referenced to pressure at standard conditions. With a 180 psig aircraft tire inflated at 70 degrees F, actual pressure at 200 degrees F was 214 psig and at -65 degrees F was 139.3 psig a change of +19% and -23%.

Thus, discrete pressure sensing systems or analog systems both without temperature compensation, could establish low pressure warning levels at about 135 to 140 psig for the 180 psig tire. Thus, discrete pressure sensing systems could not detect tires less than 40 psig underinflated (in this case) unless they were temperature compensated. An analog system with actual pressure of each tire available at the computer could compare adjacent tires and provide an alarm if tires are 15 to 20 psig different in pressure, allowing a much more sensitive low pressure detection as well as providing an alarm if any tire falls below the 135 to 140 psig absolute level. Setting these thresholds higher, of course, raises the possibility of false low pressure warnings with a tire that is cold soaked.

From the above, it may be concluded that temperature compensation of the sensing element is desirable (i.e., Temperature compensation is included in Concept C and is an available feature in the Concept B gauge.) However, airframe and tire manufacturers recommend inflation pressures without regard to temperature. In other words, a tire inflated to 180 psig in a warm climate and flown to a cold climate would drop in pressure to say 155 psi which may be below the pressure required by tire inflation charts for the next high gross weight takeoff and air must be added to the tire to bring it within the acceptable pressure range prior to that takeoff. With a temperature compensated gauge the original 180 psig pressure would be displayed and would allow a tire that is technically underinflated to go undetected.

On the high temperature side, which occurs more often due to brake heat, a temperature compensated gauge is an advantage since it allows the operator to predict what the tire pressure will be when the tire cools. This is of value so that air may be added to the warm tire if it will otherwise be underinflated when it cools. An analog system or hand held or wheel mounted gauge gets around this problem by adding a requirement that tire to tire pressure difference be no greater than 10 to 15 psi even though all are above limit because they are warm.

Thus since temperature compensated pressure indications can be misleading when tires are cold-soaked, temperature compensation appears undesirable. This limits discrete pressure monitoring systems to warning levels below cold-soaked pressures that may occur on long high altitude flights to avoid false warnings. Discrete systems can, therefore, only detect substantially underinflated tires which may be acceptable in terms of specific airline requirements for its TPI system. By comparing adjacent tires, analog systems can detect smaller pressure deviations.

Analog systems that may be used for tire pressure checks in lieu of a hand held gauge should be nearly as accurate as hand held gauges or about ± 3 psig. (This is believed to be a reasonable tolerance for a good hand held gauge including "read" tolerance). Accuracy of wheel mounted gauge tolerance (See Fig. 1) over reasonable pressure and temperature ranges is $\pm$ 4 to $\pm$ 5 psi. Tire pressure indicating analog system manufacturers claim to be able to achieve accuracies between $\pm$ 4 and $\pm$ 6 psi over reasonable temperature ranges and $\pm$ 9 to $\pm$ 10 psi over the full temperature range to -65 + 300 degrees F. These accuracies are predictions and have not been service demonstrated.

Part of the difficulty in maintaining accuracy is the error accumulation in the conversions required to bridge the tire to axle gap. Concepts D and E, for example, convert tire pressure to an electrical signal, then convert that analog signal to a frequency or digital signal to get the information across the air gap then convert back to analog for display. Each of these conversions allows possible error accumulation. Also for ease of maintenance and reduced maintenance time it is a firm design criteria that no on-aircraft calibration shall be required.

It will be difficult to maintain tolerances and accuracies for on-board systems that can be attained under optimum conditions with hand-held gauges. However, predicted accuracies appear to be sufficient to allow use of the system to detect tires that are slightly underinflated and require air to be added by the ground crews. Other concepts such as G that propose direct connection to the transducer are theoretically more accurate due to the elimination of analog to frequency conversion steps required in magnetic coupling schemes.

In ranking the theoretical accuracy obtainable with each analog approach they could be as follows:

1. Concept G - Slip Ring - Accuracy primarily limited by pressure transducer (no analog to digital conversion in wheel mounted electronics due to direct connection to pressure transducer)

2. Concept E - Magnetic Coupling - Converts analog transducer signal directly to digital word before transmission across wheel axle interface via transformer/coupler.

3. Concept D - Magnetic Coupling - Converts directly from analog transducer to frequency before transmission then converts frequency to digital word in the computer.

The load cell or LVDT concepts should be only slightly less accurate than the above. The accuracy estimates by each concept vendor do not necessarily agree with the above because aircraft production and service experience has shown that proper design of the specific circuits involved in data conversion is quite important in maintaining accuracy.

F. SUMMARY OF RELIABILITY ANALYSIS

The complete reliability analysis of cockpit TPI systems is presented in Appendix B. A summary of the reliability and Safety calculations is given in Table I, Appendix B. From Table I Appendix B it can be seen that Concepts D, E, and F (Analog) TPI systems have the highest reliability (i.e., highest R_{TPI}) and provide the most safety (i.e., lowest Q_{FW} and Q_{HAZ}). This is true even though Concepts D, E, and F designs have a higher system failure rate than Concept J (for example). Concept J's (discrete pressure sensing) TPI system has poorer reliability and safety because of the higher percentage of undetected failures and failures that cause false warnings.

The results in Table I, Appendix B show the importance of eliminating <u>all</u>, if possible, of the "Never Detected" undetected failures, i.e. all parts of the TPI system should be checked to determine that they are functional during bench tests. Also, the reliability and safety of the systems are increased by reducing the BITE and Acceptance test procedure detected, undetected failures. Therefore, it is important that as many as practical of the TPI system failures be detected failures that are annunciated to the flight crew when the failures occur. In addition, it is important that the number of failures that can cause false warnings be reduced to as few as possible.

It is noted in the study that the parts comprising the TPI systems were determined from general descriptions of the systems. Therefore, the specific type of part and the number of parts used in this study will undoubtedly not be exactly the same as actually exist in each TPI system evaluated. NO failure mode and effects analysis information was available in order to determine accurately the number of undetected failures in each category (detected during BITE, ATP or

never). Also, more detailed information of the systems is needed to more accurately determine the values for Q(T&I) and Q(MON), the probability of false indications due to transients and intermittents etc., and the probability of a false warning due to a monitor threshold tolerance error, respectively.

However, the values used in the study (they were based on an engineering judgment of the system designs from the available information) are considered to be reasonable representations of the various TPI systems. The calculations thus give an overview of the important reliability and safety aspects of TPI systems, their magnitude and how they vary depending upon significant design features, such as the number and types of parts used which affect the system failure rate and failure modes, the degree of monitoring to detect as many failures as possible, and implementation of the monitor to eliminate false warnings due to part failures and monitor warning limits being inadvertently exceeded when no low/flat tire exists.

G. MAINTAINABILITY - TIRES AND TPI SYSTEMS

1. Tire Maintenance

The fact that maintaining proper tire pressure will reduce the number of premature tire removals is well established. Aircraft tires require frequent maintenance attention. A perfectly acceptable aircraft tire can lose as much as 5% of its inflation pressure daily. Consequently, if not given daily attention, the chances of any tire becoming critically underinflated are greatly increased. To maintain optimum tire pressure, and minimize premature removals it would be desirable to check tire pressures prior to each flight.

The conventional check calling for removal of the valve cap, applying and reading a gauge, then referring to temperature conversion tables, then replacing the cap is a tedious job at best. It is costly in terms of flight line crew time. More costly because it can't always be done on schedule because of weather, route structure, etc., this being the case, the likelihood of the tires being checked on schedule diminishes. Also, tire pressures cannot be properly measured if the tire is hot, such as immediately after landing/braking when tire pressures are higher. It is a practice of some airlines to record the tire pressures of hot tires and compare relative readings. If the readings fall within 5 psi of each other, and are above the normal published inflation pressure for the tire, the inflation is considered to be acceptable.

To accomplish the tire checks, (Physically checking each tire with a pressure gauge) requires approximately an average of five to seven minutes per tire. According to airline data

sources, this time period actually defines the total time interval of the tire checking procedure. This includes the retrieval of the tire pressure gauge, Maintenance Manual reference, removal of the valve cap, reading the gauge, referring to temperature conversion tables, and replacing the cap. In addition, data recording and walking times are included. With an approximate cost of $11.00 per flight line labor hour if tires are checked each flight this results in a cost of $29.00 per day for a DC-10 series 10 based on 3.15 flights per day fleet average.

According to airline data, maintenance checks on tires average about once a day. For a design life of 50,000 landings (flights), we can find the total potential maintenance savings as given in Table 1, for typical wide body multi-wheeled transports and one typical short haul narrow body transport.

From the data in Table 1 which estimates the cost of checking tire pressures once per day for the design life of the aircraft, maintenance cost savings for wheel mounted gauges and TPI analog systems can be estimated. On the assumption that both wheel gauges and cockpit systems will prove sufficiently reliable that airlines will feel confident enough in them to eliminate daily hand held gauge checks a large portion of the tire maintenance check costs can be saved. It should take no more than 5 minutes to read and record tire pressures on a cockpit gauge for a 10 wheel aircraft or 90% savings. Nearly 80% savings could be achieved with wheel mounted gauges. Thus, on a six wheel

TABLE 1

TIRE PRESSURE MAINTENANCE COSTS

TYPE OF AIRCRAFT	DC-9	DC-10 SERIES 10	DC-10 SERIES 30	DC-10 SERIES 40	B747
HOURS PER FLIGHT	0.83	2.67	3.83	3.83	4.50
HOURS PER DAY UTILIZATION	7.02	8.42	10.93	9.68	9.50
TOTAL NO. OF FLIGHTS PER DAY	8.46	3.15	2.85	2.53	2.11
DAILY MAINTENANCE COST (BASED ON AN AVERAGE CHECK OF ONCE A DAY)	$5.50	$9.16	$11.00	$11.00	$16.50
TOTAL MAINTENANCE COST BASED ON 50,000 FLIGHTS	$32,506	$145,397	$192,982	$217,391	$390,995

FOR EXAMPLE, FOR AN 18-WHEEL B747 AIRCRAFT:

$$\text{DAILY MAINTENANCE COST} = \frac{\$11}{\text{LABOR HOURS}} \times 18 \text{ TIRES} \times \frac{5 \text{ MINUTES}}{\text{TIRE}} \times \frac{\text{HOUR}}{60 \text{ MINUTES}} = \$16.50$$

TOTAL MAINTENANCE COST BASED ON 50,000 FLIGHTS

$$= 50{,}000 \text{ FLIGHTS} \times \frac{\text{DAY}}{2.11 \text{ FLIGHTS}} \times \frac{\$16.50}{\text{DAY}} = \$390{,}995$$

aircraft with high utilization, out of the tire check cost of $32,500 a gauge could save as much as $26,000 per airplane and $29,000 for the cockpit system. On a 10 wheel aircraft the gauge saving maybe approximately $105,000 and cockpit system savings may be as high as $120,000.

Another feature of the cockpit system is that the Flight Engineer could quickly evaluate all pressures during taxi-in after landing and inform the ground crew if a low tire is discovered. This may further help in minimizing delays on quick turnarounds if a tire requires servicing and certainly makes checking tires on through-stops feasible.

2. TPI System Maintenance Costs

A total of 15 candidate systems were reviewed to determine the characteristics which most significantly impact labor and material costs to maintain the system in service. Limited information precluded an in-depth comparison of each system concept. However, it was established that the candidate systems use three basic concepts to indicate tire inflation. The first utilizes wheel mounted fill valve/gauges. This is a pressure measuring device which provides a means of quick pressure checks on walkaround. Installation of such a device does reduce maintenance costs. However, inability to display and check tire pressure when the aircraft is moving is a disadvantage.

The second employs a wheel mounted transducer to measure actual tire pressure. This concept performs by means of an inductive coupling device which transfers the electrical signal (inflation) from the wheel to the axle. This approach provides the capability of displaying the actual tire pressure. Installation of a direct reading tire pressure system, with reasonable system accuracy, would reduce the time required to check the pressure of all tires to three to five minutes, resulting in a substantial savings in operating costs (see estimates of cost above).

The third type of system measures axle deflection (or wheel speed) and can only detect a tire under inflated by a significant amount. Inability to directly read tire pressure is again a disadvantage. Installation of such a system would not yield the same savings since the amount of under-inflation required to produce a low tire indication precludes elimination of a manual pressure check.

The following tables 2A, B, C, and D present the estimated direct maintenance manhour and material costs for systems representing the major types of system. Each system type is represented by a selected concept. Therefore, the remaining concepts will be categorized according to the four system groups. Maintenance costs of the systems not specifically

TABLE 2A

ESTIMATED DIRECT MAINTENANCE MAN-HOUR AND MATERIAL COSTS — CONCEPT D; TIRE CONDITION SENSOR (ANALOG PRESSURE)

QTY	PART NOMENCLATURE	(SIMILAR EQUIP.) PART NO.	UNIT COST (EST)	UNIT MTBUR	UNIT MATERIAL COSTS/REPAIR	ACFT MMHR PER FLT HR	AIRCRAFT $ COST PER FLIGHT-HOUR*		
							MATL COST	MMHR/FLT-HR AT $11/HR	HOUR TOTAL
10	PRESS. TRANSDUCER	HYD SYS PR XMTR VT107Q	625.00	60,000	625.00	0.001	0.104	0.011	0.115
1	MICROPROCESSOR	FDAU ED742951	6,280.00	8,000	200.00	0.001	0.025	0.011	0.036
1	COCKPIT DISPLAY	AUTOPILOT IND 2587554-3	2,379.00	28,000	95.00	0.0001	0.003	0.001	0.004
10	COUPLING INDUCTIVE	LVDT GM406800-4	198.00	875,000	198.00	0.00005	0.002	0.0005	0.003
								TOTAL	0.158

*LABOR AND MATERIAL COSTS IN 1977 DOLLARS

BASED ON A 10-WHEEL SYSTEM,
TOTAL DOLLAR PER FLIGHT-HOUR FOR A 6-WHEEL SYSTEM = 0.1108
TOTAL DOLLAR PER FLIGHT-HOUR FOR A 12-WHEEL SYSTEM = 0.1816
TOTAL DOLLAR PER FLIGHT-HOUR FOR A 18-WHEEL SYSTEM = 0.2524

TABLE 2B

ESTIMATED DIRECT MAINTENANCE MAN-HOUR AND MATERIAL COSTS
CONCEPT L — WEIGHT AND BALANCE; LOW TIRE INDICATOR
CONCEPT M — WEIGHT AND BALANCE; BLOWN TIRE INDICATOR

QTY	PART NOMENCLATURE	(SIMILAR EQUIP.) PART NO.	UNIT COST (EST)	UNIT MTBUR	UNIT MATERIAL COSTS/REPAIR	ACFT MMHR PER FLT HR	AIRCRAFT $ COST PER FLIGHT-HOUR*		
							MATL COST	MMHR/FLT-HR AT $11/HR	HOUR TOTAL
10	TRANSDUCER	TRNSDCR MLG WT&B 418766	700.00	100,000	700.00	0.0002	0.070	0.002	0.072
1	NOSE GEAR CENTERED SWITCH	H14-1012	165.00	18,750	165.00	0.0001	0.009	0.001	0.010
1	ELECTRONIC UNIT	FDAU ED742951	6,280.00	8,000	200.00	0.001	0.025	0.011	0.036
1	INDICATOR UNIT	AUTOPILOT IND 2587554-3	2,379.00	28,000	95.00	0.0001	0.003	0.001	0.004
								TOTAL	0.122

*LABOR AND MATERIAL COSTS IN 1977 DOLLARS

BASED ON A 10-WHEEL SYSTEM,
TOTAL DOLLAR COST PER FLIGHT-HOUR FOR A 6-WHEEL SYSTEM = 0.0932
TOTAL DOLLAR COST PER FLIGHT-HOUR FOR A 12-WHEEL SYSTEM = 0.1364
TOTAL DOLLAR COST PER FLIGHT-HOUR FOR A 18-WHEEL SYSTEM = 0.1796

TABLE 2C

ESTIMATED DIRECT MAINTENANCE MAN-HOUR AND MATERIAL COSTS --
CONCEPT N; WHEEL SPEED SENSING

QTY	PART NOMENCLATURE	(SIMILAR EQUIP.) PART NO.	UNIT COST (EST)	UNIT MTBUR	UNIT MATERIAL COSTS/REPAIR	ACFT MMHR PER FLT HR	AIRCRAFT $ COST PER FLIGHT-HOUR*		
							MATL COST	MMHR/FLT-HR AT $11/HR	HOUR TOTAL
1	ELECTRONIC UNIT	FADU ED742951	6,280.00	8,000	2.00	0.001	0.025	0.011	0.036
1	COCKPIT DISPLAY	AUTOPILOT IND 2587554-3	2,379.00	28,000	95.00	0.0001	0.003	0.001	0.004
								TOTAL	0.040

*LABOR AND MATERIAL COSTS IN 1977 DOLLARS

BASED ON A 10-WHEEL SYSTEM,
TOTAL DOLLAR PER FLIGHT-HOUR FOR A 6-WHEEL SYSTEM = 0.032
TOTAL DOLLAR PER FLIGHT-HOUR FOR A 12-WHEEL SYSTEM = 0.049
TOTAL DOLLAR PER FLIGHT-HOUR FOR A 18-WHEEL SYSTEM = 0.064

TABLE 2D

ESTIMATED DIRECT MAINTENANCE MAN-HOUR AND MATERIAL COSTS
CONCEPT H — TIRE DEFLATION WARNING SYSTEM (DISCRETE PRESSURE)

QTY	PART NOMENCLATURE	(SIMILAR EQUIP.) PART NO.	UNIT COST (EST)	UNIT MTBUR	UNIT MATERIAL COSTS/REPAIR	ACFT MMHR PER FLT HR	AIRCRAFT $ COST PER FLIGHT-HOUR*		
							MATL COST	MMHR/FLT-HR AT $11/HR	HOUR TOTAL
10	WHEEL-MOUNTED PRESSURE SWITCH	SWITCH PRESS HIGH (HYD) 1105 P24	116.00	80,000	30.00	0.001	0.00375	0.01375	0.0175
10	COUPLING INDUCTIVE	LVDT GM406800-4	198.00	875,000	198.00	0.00005	0.0025	0.0005	0.003
1	COCKPIT DISPLAY	AUTOPILOT IND 2587554-3	2,379.00	28,000	95.00	0.0001	0.003	0.001	0.004
1	COMPUTER	FDAU ED742951	6,280.00	8,000	200.00	0.001	0.025	0.011	0.036
								TOTAL	0.0605

*LABOR AND MATERIAL COSTS IN 1977 DOLLARS

BASED ON A 10-WHEEL SYSTEM,
TOTAL DOLLAR PER FLIGHT-HOUR FOR A 6-WHEEL SYSTEM = 0.0523
TOTAL DOLLAR PER FLIGHT-HOUR FOR A 12-WHEEL SYSTEM = 0.0646
TOTAL DOLLAR PER FLIGHT-HOUR FOR A 18-WHEEL SYSTEM = 0.0769

analyzed should be similar to the maintenance costs typical of its group. Wheel mounted gauges were not analyzed as they are generally not repairable and are relatively inexpensive.

Based on the actual cost estimates for a 10-wheel system, the costs for the 6-wheel system, 12-wheel system and 18-wheel system can be calculated and compared. Estimated costs were determined by choosing equipment judged similar to the new equipment. Items chosen as similar were limited to those presently installed on DC-9 and DC-10 aircraft, thus providing actual maintenance cost data.

Table 3 presents the total maintenance cost for each major system type. The cost can be found providing X, Y, and Z are given. X denotes the total number of hours per flight. Y gives the total dollar per flight hour. Z represents a design life of 50,000 flights. Determination of maintenance cost depends on the complexity of the TPI system, the type of aircraft (number of wheels), and the total number of flights (average flight length). A typical maintenance cost calculation for a TPI system is as follows:

Type of TPI system = Concept L (indirect weight and balance)

Type of aircraft system = L-1011 (10-wheel system)

Typical design life landings (flights) = 50,000

Hours per flight for L-1011 = 2.34

Components of Concept L	$/hr for 10-wheel system
1. Electronic unit	.036
2. Indicator unit	.004
3. Transducer	.072
4. Nose gear center switch	.010

Total cost for maintaining Concept L = $.122/hour.

(Note that item 3 will change in value in different wheel configurations since one transducer per wheel is required).

Total maintenance cost of Concept L for L-1011

= 2.34 hours/flight x 50,000 flights x $.122/hour

= $14,274.

A different maintenance cost is similarly obtained for each aircraft and concept. Since each type of aircraft has a different hours per flight schedule, and each concept consists of different components, thus different maintenance costs are derived for each system. With the calculation of the total maintenance cost, each concept can be compared for different wheel configurations which is shown in Table 3.

The higher cost of maintenance of direct analog reading systems will be offset by the potential reduction in tire maintenance costs discussed earlier in this section. None of these costs can be recovered by the weight and balance, wheel speed and discrete pressure sensing approaches, since daily hand tire pressure checks will still be required.

H. INSTALLATION

The relative difficulty of installation is a major area of difference between specific concepts and concept groups. In general, the most difficult to install are the analog pressure systems; the next most difficult the discrete pressure sensing systems; the weight and balance system blown tire indicating systems being relatively more easy despite the requirement to rewire bogie beam transducers when retrofitting existing wide body aircraft; and the easiest to install being the proposed wheel speed system which bypasses the need to install new sensors or rewire existing ones.

The heart of the analog pressure indicating systems installation problem involves the transferral of information from the rotating wheel to the axle which is required, whether the aircraft is moving or static. The wheel hub is so far the most promising approach.

Wheel Hub

Although detailed wheel hub drawings were not available for Boeing or Lockheed aircraft, hub installations on all Boeing, Lockheed and Douglas aircraft covered by this study appear feasible. Figure 15 shows a potential installation on a B-747 which is typical of the installation of this system concept on a DC-10. The L-1011 installation is more difficult because of the type of antiskid transducer used but at least one manufacturer showed a potentially satisfactory installation mounting the transformer/coupler on the face of the existing antiskid transducer. The TPI transformer/coupler can be installed in a DC-9 axle by recessing the antiskid transducer about 2" further in the axle and lengthening the transducer coupler. The extra space thus created between the antiskid transducer and hub cap can house the TPI transformer/coupler or slip-ring. In each case, new hub caps would generally be required.

TABLE 3

TOTAL MAINTENANCE COSTS FOR COCKPIT TPI SYSTEMS
DESIGN LIFE OF AIRCRAFT

	CONCEPT D (ANALOG PRESSURE)	CONCEPTS L AND M (INDIRECT WEIGHT AND BALANCE)	CONCEPT N (WHEEL SPEED)	CONCEPT H (DISCRETE PRESSURE)
6-wheel	X = 0.85 Y = 0.1108 Z = 50,000 Cost = X x Y x Z = $4,709	X = 0.85 Y = 0.0932 Z = 50,000 Cost = X x Y x Z = $3,961	X = 0.85 Y = 0.04 Z = 50,000 Cost = X x Y x Z = $1,700	X = 0.85 Y = 0.0523 Z = 50,000 Cost = X x Y x Z = $2,223
10-wheel	X = 2.67 Y = 0.158 Z = 50,000 Cost = X x Y x Z = $21,093	X = 2.67 Y = 0.122 Z = 50,000 Cost = X x Y x Z = $16,287	X = 2.67 Y = 0.04 Z = 50,000 Cost = X x Y x Z = $5,340	X = 2.67 Y = 0.0605 Z = 50,000 Cost = X x Y x Z = $8,077
12-wheel	X = 3.83 Y = 0.1816 Z = 50,000 Cost = X x Y x Z = $34,776	X = 3.83 Y = 0.1364 Z = 50,000 Cost = X x Y x Z = $26,121	X = 3.83 Y = 0.04 Z = 50,000 Cost = X x Y x Z = $7,660	X = 3.83 Y = 0.0646 Z = 50,000 Cost = X x Y x Z = $12,371
18-wheel	X = 4.50 Y = 0.2524 Z = 50,000 Cost = X x Y x Z = $56,790	X = 4.50 Y = 0.1796 Z = 50,000 Cost = X x Y x Z = $40,410	X = 4.50 Y = 0.04 Z = 50,000 Cost = X x Y x Z = $9,000	X = 4.50 Y = 0.0769 Z = 50,000 Cost X x Y x Z = $17,303

Definitions: X = Total number of hours per flight
Y = Total dollar per flight hour
Z = Total number of flights based on a design life
Cost = Total maintenance cost

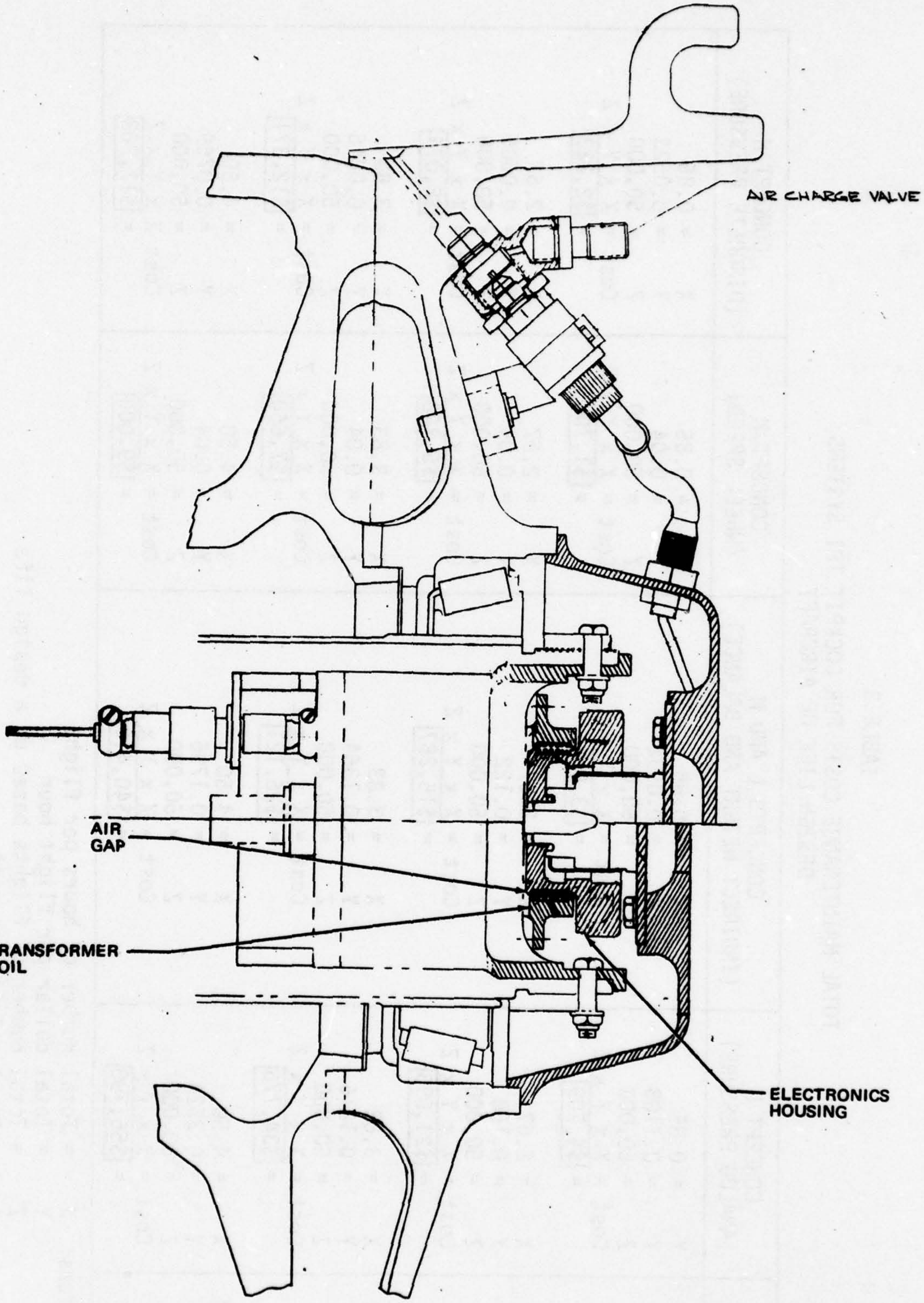


FIGURE 15. TYPICAL TPI TRANSFORMER COUPLER INSTALLATION

In evaluating the feasibility of installing such systems on the B-707/727/737 Boeing engineers saw no insurmountable difficulties, but a number of parts would have to be modified or replaced, such as:

"1. New hub caps would be required; existing hub caps do not have space available for the transformers.

2. Antiskid transducer drives would be new in order to match the hub cap geometry.

3. Antiskid transducer mounts would be changed to gain additional axial clearance.

4. New or remachined outboard wheel halves would be required to provide mounting provisions for the sensors and associated electronics.

5. Axle rework would be required to provide additional or larger windows for routing the extra wires.

In addition to the above, the early B-707's would have to be retrofitted with the Mark II antiskid system, and early B-737's would have to be changed from the Goodyear to the Mark III system."

After reviewing the above with several TPI vendors the fourth (4) requirement may not be necessary. Existing wheel ports can be used with combined functions and electronics can be packaged at the transducer or in the hub.

<u>Inboard Wheel Area</u>

The primary objection to hub mounted transformer/coupler schemes has been that mechanics would be required to disconnect and reconnect an electrical connector anytime a hub cap was removed. The hub cap may then be placed on the ground where water could get into the hub and open connector. Also, another connector would be required in the hub cap if a slip ring is used which makes a slip ring more objectionable.

To overcome these objections the inboard wheel area was evaluated for the coupling device mounting. The primary coil might be mounted around the axle attached to it. The wires to the primary coil would go to the bogie beam or strut by going underneath the brake assembly. The secondary coil would be mounted on the inboard wheel half and mated with the primary coil by axial or radial clearance. The mounting area can be seen in Figure 16. Thus, every time the wheel is removed the wheel mounted TPI components need not be disturbed. The disadvantage of this inboard axle area is the higher temperature and high brake dust contamination due to the close proximity to the brake. There is also inadequate

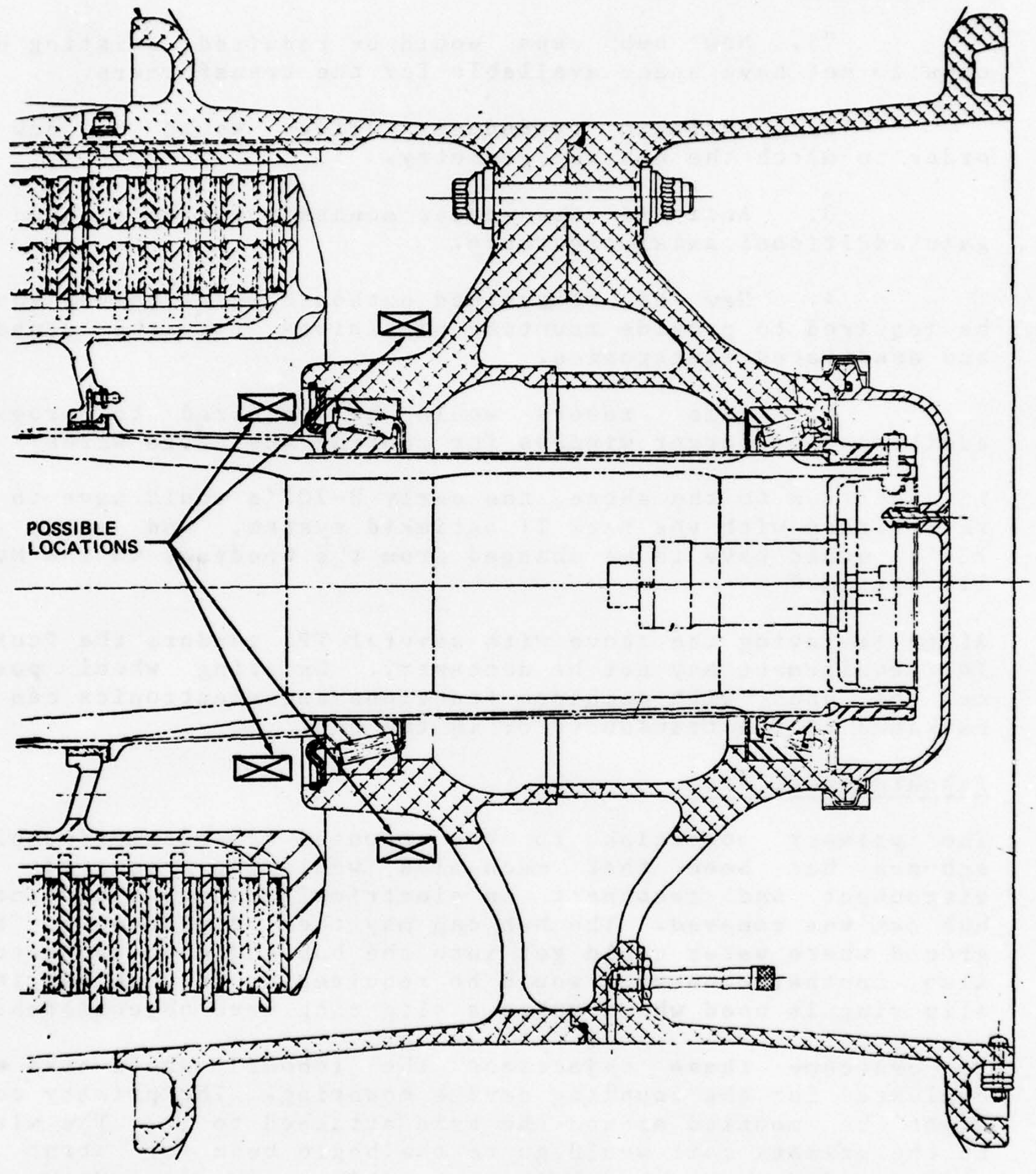


FIGURE 16. ALTERNATE INBOARD WHEEL INSTALLATION LOCATION

space available on several of the study aircraft in this location.

The alternate inboard location is shown in Figure 17. Most of the discrete pressure measuring system concepts proposed an installation such as this. Other than the exposure to tire debris damage this is a relatively easy installation that does not require disconnecting equipment when the hub cap or tire is removed.

The approach shown in Figure 17 is for a system that provides readout only when the aircraft is in motion via periodic alignment of the primary and secondary coils. This installation could be made to read pressure continuously (with aircraft static or in motion) if the secondary coil is in the form of a continuous ring mounted on the inboard wheel flange, analog pressure or discrete pressure (switch) could be read at any time.

One significant advantage in having the ability to read tire pressure with the aircraft static (it is, of course, required if analog readout is desired by maintenance personnel) is in troubleshooting the TPI system. With a system that has primary and secondary coil alignment once every tire revolution it may be required to jack the gear and spin the wheel to determine if the system is operating with the aircraft parked. This could be cumbersome and time consuming. With a continuous readout with the aircraft parked maintenance should be facilitated.

Installation Cost

Man-hour estimates to install two different type pressure indicating systems on DC-8, -9, -10, B-747, 737, 727, 707, and L-1011 aircraft have been made.

It must be noted that the man-hour estimates are predicated on the theory of remove-and-replace or clamp-on parts. Using this as a guide, basic modification estimates were possible. The addition of one conduit line to transport the wiring from base of the strut to the wing on the main gears and nose gear was used for the purpose of this estimation.

Installation and modification to the wing and fuselage is basically the same for similar size aircraft of different manufacture. Individual differences of each type of aircraft have not been considered in this estimate. It was assumed that avionic rack space was available and no major rework required in either the overhead panel or Flight Engineer's console.

For the purpose of this feasibility study the number of wheels to be modified per aircraft was determined at this

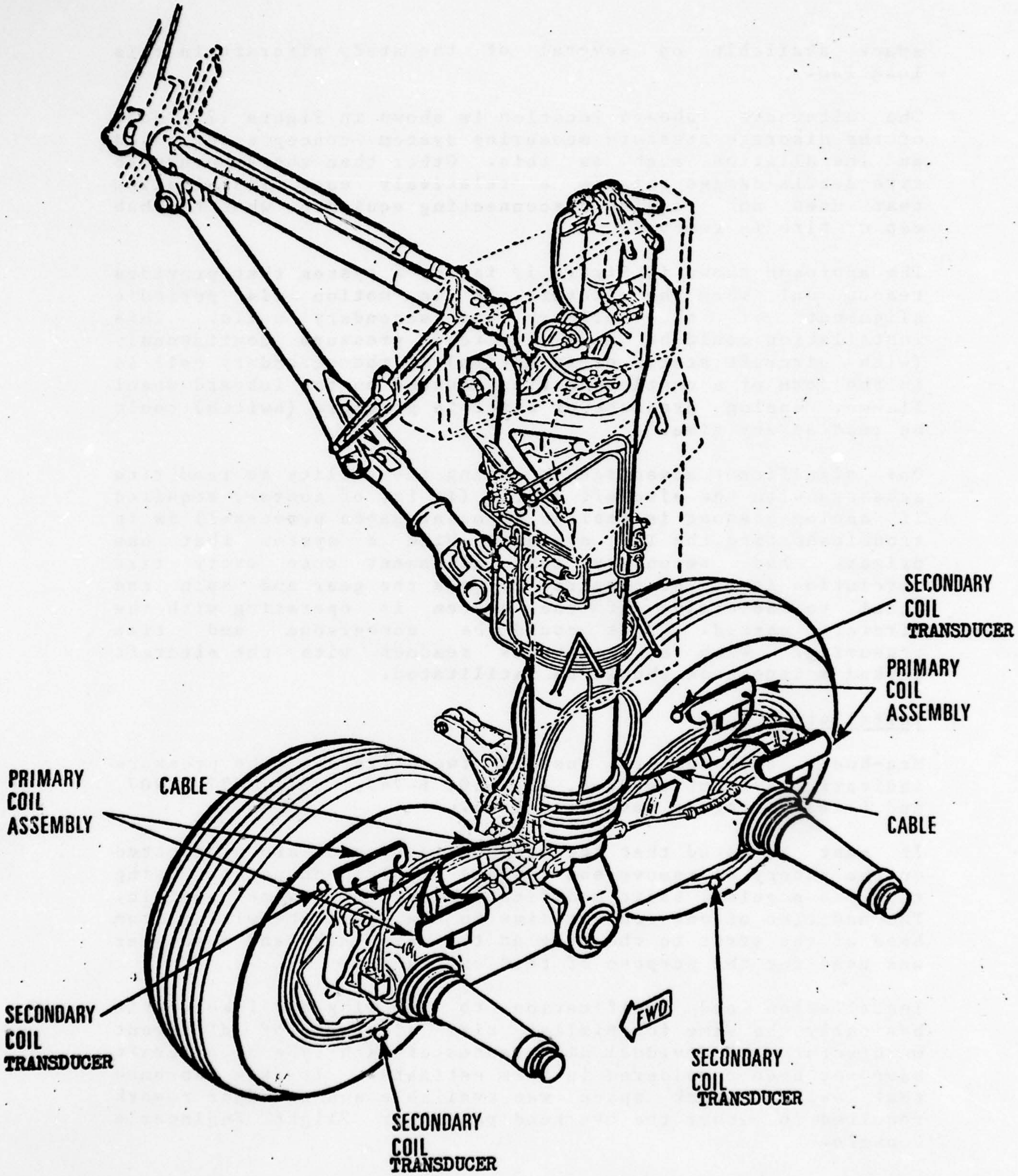


FIGURE 17. INBOARD WHEEL INSTALLATION (ALTERNATE TO FIGURE 16)

time to be the major difference (excluding size) in modification time between the various aircraft.

It was estimated that 18 man-hours or 9 elapsed hours will be required to remove/modify (wheel and truck assembly) and install each wheel. This time is also the most variable, as a firm method of modification has not been determined at this time. Installation costs are summarized in Table 4.

Three factors must be considered in the man-hour estimation quotes.

1. The aircraft has been placed in a maintenance condition. (No downtime cost.)

2. Unique access times are not reflected in these estimates.

3. Times are estimated on a "third-ship" knowledge of the job and are actual working times. Other users should adjust these time estimates for their individual labor time rates for breaks, meals, set-up, shift changes, manpower loading, and productivity practices. To obtain approximate dollar cost, $47 per labor hour was used which carries full overhead costs.

To install a modified weight and balance system having a blown tire detection feature on a B-747, for example, requires rewiring of both power and signal leads to each main gear transducer. This requires the addition of wires across the aircraft between wing and body gear. One airline planning to make the change for a trial installation on a B-747 freighter estimated the rewiring and other installation would take approximately 180 hours. The cost for B-747 weight and balance Blown Tire Indicator installation would be approximately $47/hr x 180 hours = $8,460. A similar rewiring is required for the L-1011 weight and balance system modification which has been estimated at approximately 95 hours or $4,465.

TABLE 4

INSTALLATION COSTS
COCKPIT TPI SYSTEMS

ANALOG OR DISCRETE PRESSURE	TOTAL MAN-HOURS	ELAPSED HOURS	TOTAL LABOR COST ($47 PER MAN-HOUR)
B747	491.0	96.0	23,077
DC-10-30/40	377.0	72.0	17,719
DC-10-10, L-1011	337.0	72.0	15,839
DC-9, B737, B727	207.0	60.0	9,729
DC-8, B707	303.0	60.0	14,241
ULTRASONIC OR RADIO FREQUENCY			
B747	187.0	72.0	8,789
DC-10-30/40	161.0	48.0	7,567
DC-10-10, L-1011	157.0	48.0	7,379
DC-9, B737, B727	104.0	40.0	4,888
DC-8, B707	123.4	40.0	5,800
WHEEL SPEED SENSING			
B747	70.0	27.0	3,295
DC-10-30/40	60.0	18.0	2,839
DC-10-10, L-1011	59.0	18.0	2,768
DC-9, B737, B727	39.0	15.0	1,833
DC-8, B707	46.0	15.0	2,176

I. TPI SYSTEMS HARDWARE COST

Approximate costs for wheel mounted gauges and devices and cockpit indicating systems have been obtained and are shown in Table 5. The prices are grouped by major system category. The prices are in most cases budgetary and are generally on the high side of the prices obtained for each system and assume quantity orders.

Cost of spares has not been estimated or calculated. Based on system costs each airline may apply their factors to estimate spare costs. It should be noted, however, that the specific device or system design has some impact on spares costs. For example, if fill valve/gauges are purchased with color coded dial faces, an airline may have to stock two and in some cases three (DC-10-30/40) part number gauges per aircraft type whereas without color coding one gauge may be purchased for an entire fleet. This is also true for pressure switch systems such as Concept C, H, I, J, and K which require a pressure switch for each different pressure warning level. In these cases the spares cost should be relatively higher than for a pressure transducer that may be installed at any wheel location.

J. TPI DEVICE AND SYSTEM WEIGHT SUMMARY

The tire pressure indicating system device and system weights are given in Table 6. The hardware weights are relatively accurate based on well known weights. The wiring weights are rough estimates. In general the systems in each major category are approximately equal in weight; little variation is shown. One variation in wiring weight should be noted with Concept H and J which require 4 wires per wheel instead of 2 as in all other systems. The actual wiring weight would be higher for these two concepts than is shown for the overall category.

TABLE 5. TPI HARDWARE COST

Concept \ Price	Per 6-wheel acft	Per 10-wheel acft	Per 18-wheel acft
Concepts A and B Fill Valve/Gage (Approx $125 ea)	$750	$1,250	$2,250
Concept C Switch ~ $100 ea/wheel Interrogator ~ $500 ea	 $600 (6 wheels) $1,000 (2 units)	 $1,000 $1,000	 $1,800 $1,000
Concepts D, E, F, G Analog Pressure	$17 → 19,000	$22 → 25,000	$30 → 34,000
Concepts H, I, J, K Discrete Pressure	$10 → 13,000	$15 → 18,000	$22 → 26,000
Concepts L and M Add on only to existing weight and balance system	N/A	$6,000*	$8 → 9,000
Concept N Wheel Speed	$6,000	$8,000	$10,000

NOTE: Cost estimates are budgetary and in most cases have been arbitrarily inflated to allow for possible price increases through 1979.

*Estimate only.

TABLE 6

WEIGHT SUMMARY; TPI CANDIDATE SYSTEMS

SYSTEM CONCEPTS	6-WHEEL AIRCRAFT		10-WHEEL AIRCRAFT		18-WHEEL AIRCRAFT	
	POUNDS	KILOGRAMS	POUNDS	KILOGRAMS	POUNDS	KILOGRAMS
Concepts A, B and C						
Hardware Weight	1.50	0.68	2.50	1.14	4.50	2.05
Wiring Weight	—	—	—	—	—	—
Total Weight	1.50	0.68	2.50	1.14	4.50	2.05
Concepts D, E, F and G						
Hardware Weight	19.30	8.77	24.50	11.04	34.90	15.86
Wiring Weight	15.00	6.82	20.00	9.09	25.00	11.36
Total Weight	34.30	15.59	44.50	20.23	59.90	27.22
Concepts H, I, J and K						
Hardware Weight	11.88	5.40	15.40	7.00	22.44	10.20
Wiring Weight	15.00	6.82	20.00	9.09	25.00	11.36
Total Weight	26.88	12.22	35.40	16.09	47.44	21.56
Concept N						
Hardware Weight	4.00	1.76	5.00	2.27	7.00	3.18
Wiring Weight	3.00	1.36	4.00	1.82	5.00	2.27
Total Weight	7.00	3.12	9.00	4.09	12.00	5.45
Concepts L and M						
Hardware Weight	8.04	3.65	9.40	4.27	12.12	5.51
Wiring Weight	8.50	3.86	11.00	5.00	13.50	6.14
Total Weight	16.54	7.51	20.40	9.27	25.62	11.65

IV. COST-EFFECTIVENESS STUDY AND RESULTS

In attempting to determine the cost-effectiveness of wheel mounted fill valve/gauges, concepts A, B, and C, it was very difficult to determine what damage costs might be avoided by their use. There are some in the aircraft/airline industry that believe that wheel mounted gauges will help avoid a significant percentage of damage costs by encouraging closer monitoring of tire pressures. Also, as mentioned in the Maintainability Section the fill valve/gauges can provide a significant reduction in tire maintenance cost by reducing the time for tire pressure checks once the reliability of the devices is demonstrated. Due to the relatively low cost of the gauges, almost any reduction in maintenance or damage cost resulting from their use will make the gauges very cost-effective. It is, therefore, a general conclusion of this study that fill valve/gauges are cost-effective for all the study aircraft if for no other reason than the possible reduction in tire pressure check times.

Most of this study effort is concentrated on cockpit systems cost-effectiveness (i.e.) effectiveness in avoiding tire failures after leaving the "gate". The study was unable to quantify what percentage of the damage cost resulting from tire problems (underinflation) occurred after the aircraft left the gate. Had this been possible a relative cost effectiveness comparison between wheel mounted fill valve/gauges and cockpit systems could have been made. There were, however, some well documented instances where tire pressures were checked at the ramp and found to be o.k. and the aircraft experienced a severe tire failure on takeoff. Therefore, the cost-effectiveness of cockpit systems has been considered without regard to how much of those costs could have been eliminated by wheel mounted fill/valve gauges.

TPI Hardware Costs

The total cost of a TPI system installation on a given aircraft is the sum of the hardware cost, installation cost and maintenance cost. Each group of system concepts has been evaluated with the results given in Table 7. The relative complexity of the analog systems and more difficult installation make a substantial cost difference between them and, for example, the concept N wheel speed approach. All costs are based on a 50,000 landing aircraft design life.

Damage Costs Avoided

A direct comparison is made between the cost of each system type and the damage cost which can be avoided by the installation of a TPI system. The damage cost calculations

TABLE 7

COST OF COCKPIT TIRE PRESSURE INDICATING SYSTEMS PER AIRCRAFT

SYSTEM CONCEPTS	COSTS ($)	AIRCRAFT								
		DC-8	DC-9	DC-10-10	DC-10-30/40	B707	B727	B737	B747	L-1011
ANALOG PRESSURE (CONCEPT D,E,F,G)	HARDWARE COST	25,000	19,000	25,000	27,000	25,000	19,000	19,000	34,000	25,000
	INSTALLATION COST	14,241	9,729	15,839	17,719	14,241	9,729	9,729	23,077	15,839
	MAINTENANCE COST	21,567	4,598	21,093	34,776	21,962	7,978	5,485	56,790	18,486
	TOTAL COST	60,808	33,327	61,932	79,495	61,203	36,707	34,214	113,867	59,325
INDIRECT WEIGHT * AND BALANCE (CONCEPT L,M)	HARDWARE COST	N/A	N/A	N/A	N/A	N/A	N/A	N/A	9,000	6,000
	INSTALLATION COST	N/A	N/A	N/A	N/A	N/A	N/A	N/A	8,460	4,465
	MAINTENANCE COST	N/A	N/A	N/A	N/A	N/A	N/A	N/A	40,410	14,274
	TOTAL COST	N/A	N/A	N/A	N/A	N/A	N/A	N/A	57,870	24,739
WHEEL SPEED (CONCEPT N)	HARDWARE COST	8,000	6,000	8,000	8,500	8,000	6,000	6,000	10,000	8,000
	INSTALLATION COST	2,176	1,833	2,768	2,839	2,176	1,833	1,833	3,295	2,768
	MAINTENANCE COST	5,460	1,660	5,340	7,660	5,560	2,880	1,980	9,000	4,680
	TOTAL COST	15,636	9,493	16,108	18,999	15,736	10,713	9,813	22,295	15,448
DISCRETE PRESSURE (CONCEPT H,I,J,K)	HARDWARE COST	18,000	13,000	18,000	20,000	18,000	13,000	13,000	26,000	18,000
	INSTALLATION COST	14,241	9,729	15,839	17,719	14,241	9,729	9,729	23,077	15,839
	MAINTENANCE COST	13,172	3,664	12,883	19,265	13,414	6,358	4,371	25,403	11,291
	TOTAL COST	45,413	26,393	46,722	56,984	45,655	29,087	27,100	74,480	45,130

*THIS COST IS ONLY FOR ADD-ON TO EXISTING SYSTEMS. DC-8, DC-9, B707, B727, B737 DO NOT HAVE EXISTING SYSTEMS. DC-10 DOES BUT THE WEIGHT AND BALANCE SYSTEM MANUFACTURER IS NOT OFFERING BLOWN TIRE INDICATOR HARDWARE.

and data are thoroughly explained in Appendix A. The important conclusion arrived at in Appendix A, in addition to the damage cost estimates for each aircraft type, is that a good cockpit TPI system should be able to reduce damage costs by 65.7%. (As mentioned above, the study was not able to determine what percentage of this figure the fill valve/gauge might contribute.) The data in Table 8 shows the cost of each system type compared to the damage cost avoided. The damage cost avoided was obtained by multiplying the damage cost per departure for each aircraft x 50,000 landing design life x (.657).

The conservative damage cost numbers in Appendix A are believed justified since tire improvements and improved maintenance practices should keep these costs down in the future compared with the data derived from the 1973-1976 time period. Even with the more conservative damage cost figures some aircraft such as the DC-10 and B-747 appear to clearly benefit from a TPI system while aircraft such as the B-727 would not from a strictly damage cost avoidance approach.

TABLE 8

ESTIMATED AIRCRAFT DAMAGE COSTS AVOIDED BY COCKPIT TPI SYSTEMS

AIRCRAFT	COST OF ANALOG PRESSURE ($)	COST OF INDIRECT WEIGHT AND BALANCE ($)	COST OF WHEEL SPEED ($)	COST OF DISCRETE PRESSURE ($)	DAMAGE COST AVOIDED ($)
DC-8	60,808	N/A	15,636	45,413	37,778
DC-9	33,327	N/A	9,493	26,393	11,826
DC-10-10	61,932	N/A	16,108	46,722	128,115
DC-10-30/40	79,495	N/A	18,999	56,984	128,115
B707	61,203	N/A	15,736	45,655	8,870
B727	36,707	N/A	10,713	29,087	3,942
B737	34,214	N/A	9,813	27,100	14,454
B747	113,867	57,870	22,295	74,480	167,864
L-1011	59,325	24,739	15,448	45,130	23,652*

*NO L-1011 DATA WERE AVAILABLE SO THE FLEET AVERAGE OF $0.72 DAMAGE COST PER DEPARTURE WAS USED.

Maintenance Cost Savings

Three of the proposed system concept groups, i.e., the indirect weight and balance system, the wheel speed system and the discrete pressure systems will not produce any maintenance cost savings. The analog systems that can read actual tire pressure do offer cost savings by reducing tire check times (see Maintainability section). The maintenance cost calculations are based on a 50,000 landing design life and with the assumption that tire pressures are checked once a day. Thus, the average number of flights per day for each aircraft fleet is used to determine the number of times tires are checked which then gives potential maintenance cost that could be saved. By this method a DC-9 that averages 8 flights per day will have a significantly lower cost saving than a DC-10 series 30/40 with a little over two flights per day.

Realistically all hand tire checks will not be eliminated on a TPI equipped airplane. Therefore a column was added in Table 9 that gives an arbitrary 50% reduction in maintenance costs. These maintenance costs can be factored by a potential TPI user based on planned system usage.

TABLE 9. POTENTIAL MAINTENANCE COST SAVING FOR ANALOG TPI SYSTEMS

AIRCRAFT	COST OF ANALOG PRESSURE CONCEPT ($)	MAINTENANCE SAVING COST ($)	50 PERCENT OF MAINTENANCE SAVING COST ($)
DC-8	60,808	186,180	93,090
DC-9	33,327	32,500	16,250
DC-10-10	61,932	145,400	72,700
DC-10-30/40	79,495	193,000	96,500
B707	61,203	163,570	81,785
B727	36,707	49,640	24,820
B737	34,214	42,050	21,025
B747	113,867	391,000	195,500
L-1011	59,325	106,020	53,010

Other Costs

As noted in the hardware cost section, TPI system spares costs have not been included. These can be traded off against delay and cancellation costs which were also not specifically included due to insufficient information. From the one airline that did report these costs, however, delay and cancellation costs appear to be as significant if not more so than damage costs. Both spares costs and delay and cancellation costs that might be avoided should not be overlooked by an airline when considering the purchase of TPI systems.

V. RESULTS OF ANALYSIS OF COCKPIT INDICATING SYSTEMS

Concept D - Tire Condition Sensor (Analog Pressure - Cockpit)

It should be noted that this is a sampling system that takes 2.5 to 3.0 seconds to sample ten wheels so the maximum indication delay could be 3 seconds after exceeding a threshold pressure criterion on takeoff roll. Design availability status is as follows:

1. System testing limited to laboratory. Hardware is designed and built for DC-10 and B-747 wheel and hub assembly. Accuracy should be proven in actual aircraft test. Accuracy depends on pressure transducer selected and stability of rotating electronics with temperature and component aging.

2. Microprocessor based system with analog data processing should provide maximum rejection of false warnings. Detailed failure mode and effects analysis must be completed to ensure that specific component failure in rotating (wheel) electronics do not cause undetectable false warnings. (This comment applies for nearly every system analyzed.)

Concept E - Tire Pressure Indication (Analog Pressure - Cockpit)

This system was claimed by the manufacturer to offer the highest system accuracy at lowest cost of all the analog approaches. High accuracy might be achieved by immediate analog to digital word conversion in the rotating (wheel) electronics proposed for this system. Accuracy would have to be proven by test. The system is at the conceptual stage of development.

Concept F - LVDT System (Analog Pressure - Cockpit)

Of the analog pressure systems analyzed, the LVDT or load cell actuated bellows approach may have the highest error due to transducer tolerance and bellows hysteresis. Overall readout accuracy should be acceptable, however, because system is simpler by eliminating need for electronic circuits in the hub cap; (required by Concepts D and E) system drawback, appears however to be the requirement to bring tire air into the hub area across the hub cap wheel interface.

Concept G - Tire Pressure Indication Via Slip Rings (Analog Pressure - Cockpit)

This system proposes a slip ring for bridging the wheel to axle gap. A complete evaluation of the suitability of slip rings for this application is considered beyond the scope of

this report. However, the manufacturer has claimed actual small aircraft and highway vehicle experience with good results.

No information was provided to determine if a four contact slip ring is required for a strain gauge transducer, or two contacts for a variable resistance potentiometer transducer.

Two electrical connectors might be required to bridge the hub cap for a slip ring since the slip rings should not be separated when the hub cap is removed as primary and secondary coils in a transformer/coupler installation.

Although not claimed by the manufacturer a direct transducer connection without intervening data conversions and with digital noise filtering potentially may offer the higher system accuracy.

Concept H - Tire Deflation Warning (Discrete Pressure - Cockpit)

This particular design represents one of the most promising of the discrete pressure sensing systems that were evaluated. The specific pressure switch design is quite simple and rugged and the electronic circuits have been designed with attention to avoidance of false warnings. This attention to eliminating false warnings goes quite far toward removing the main objections raised about discrete sensing systems in this study.

Hardware has been fully developed and laboratory tested. The basic pressure switch design has been in production for highway vehicle systems.

Sensitive features of this system are that it requires 4 wires per wheel (instead of 2 for most other systems), it cannot provide an indication statically and in flight, underinflation must exceed 30 + psi before detection, and it is difficult to determine if the system is working properly (able to correctly warn of an underinflated tire). (Preliminary results from a similar system concept in test on a DC-10 have substantiated the concerns).

Concept I - Differential Valve (Discrete Pressure - Cockpit)

This system is potentially one of the simpler approaches with a differential valve at the tire fill valve with a sight indicator showing when the tire is low and the valve has tripped. The tendency of the system to be susceptible to false warnings has been recognized by adding a pressure transducer that will be connected to the computer via slip rings when the differential valve has tripped due to low tire pressure.

The system is at the conceptual stage of development. A somewhat similar differential valve driving a sight or "pop-up" indicator is in production for automobiles and highway vehicles.

The drawbacks to the approach are those typical of most discrete systems in that it is difficult to determine if the system is reliably and correctly responding to a low tire indication and the tire must be substantially underinflated before a warning is given. Although this system indicates when the aircraft is static or moving it may not provide a reliable indication when the tire fails explosively. Tire air is required to energize the bellows to engage the slip rings. Sufficient air may not be available considering valve response time and time to read transducer signal before the tire fails explosively. Also the system is somewhat complicated by the addition of the pressure transducer which seems to be valuable for prevention of false warnings but the transducer information is only available when the tire is underinflated.

Concept J - Discrete TPI System (Direct Pressure - Cockpit)

This system has been developed for highway vehicles. The approach is well thought out but it has not been seriously proposed for aircraft.

Concept K - Discrete TPI System Via Hub Mounted Switches (Cockpit)

This system is in operation on many highway vehicles and is quite simple. It has not been proposed for aircraft.

Concepts L, M, and O - Weight and Balance System Approach

The technical approach of using differential bogie strain to indicate a substantially underinflated tire is acceptable. This system coupled with tire fill/valve gauges on each tire may be an optimized solution to minimizing the problem of tire failures and associated costs of aircraft damage. However, adaptation and implementation of such systems should consider the following aspects of the concept.

1. Sensitivity claims made (Concept O) of 5% underinflation static and 20% dynamic should be substantiated. Service evaluation by a major airline the practical limits to be 30% static and 50% dynamic to avoid false warnings.

2. Very close attention must be paid to the elimination of all false warnings in specific circuits (see Reliability Analysis in Appendix B). These systems have a higher probability of false warnings than several of the

analog pressure concepts (D, E, F). It appears that Concept M has not seriously considered the requirement.

3. The present most significant objection to adding blown tire indication to existing weight and balance systems is the poor reliability of present systems. With calibration drift, transducer moisture contamination some airlines have become discouraged with the systems and are deactivating them. New efforts on the part of existing manufacturers and new manufacturers are offering promising solutions to these problems which make this approach still worthy of consideration.

Concept N - Wheel Speed Approach

This concept offers the most cost-effective means of detecting underinflated tires while the aircraft is rolling. The specific circuit design proposed appears excellent and although monitoring to avoid false warnings has not been included in the initial design it appears to be easily added.

The key to the workability of this concept is whether rolling radius changes due to tire underinflation substantially exceed normal changes between tires due to tread wear, carcass growth and different manufacturers' tire size and tire spring rate variations. To avoid the effects on tire rolling radius due to runway crown, adjacent tires or tires on the same strut should be compared. This makes this approach mostly useful on 4 wheel trucks where tires diagonally located can be compared. The problem with comparing adjacent tires (on same axle) is that the underinflation in one tire tends to increase the load on the mated tire and therefore its deflection which tends to minimize the difference in rolling radius between the two. A worst case study of tire rolling radius variables is in progress using NASA Report TR-64 as a technical basis with specific tire information from tire manufacturers. The results of this study will be included in part II of this TPI study report which covers flight test of TPI systems and the reasons for selecting systems to be tested.

This concept has been taxi tested with nominal (same) tires on a B-727. A firm indication was obtained at 15 kts taxi speed with a tire 50% underinflated. Across-aircraft tire pairing was used. As noted above across-aircraft pairing is subject to errors during aircraft turning maneuvers, due to runway crown, and differential gear loading in a cross wind. Further tests are planned.

VI. CONCLUSIONS

Tire pressure indicating systems are technically feasible for all the study aircraft and are potentially cost effective, at present, for several of the study aircraft. Beyond strict cost-effectiveness, cockpit pressure indicating systems are carefully designed to avoid false warnings can reduce aircraft damage exposure and increase ground operational safety through early warning of tire problems that develop after pushback from the terminal gate, taxi to take-off, take-off, etc.

This favorable conclusion must be tempered by several factors. First, the data used in the cost-effectiveness study, although conservative, came from a period (1973-1976) in which a high tire incident rate was experienced. At least two of the six airlines reporting showed a substantial reduction in tire failure and damage cost rates since 1975. Higher awareness of the need for and implementation of good tire maintenance programs can reduce the need for TPI systems. Secondly, the landing gear system and aircraft manufacturers are constantly improving the rolling assemblies of aircraft through stronger wheels and higher ply rated tires creating improved tire operational margins. Finally, there are other studies being conducted into means and cost-effectiveness of improving tires so that they are capable of accepting high overloads for short periods. The development of internal or external tire safety devices for the development of the ability of a deflated tire to support a high percentage of rated load for a takeoff and/or landing cycle could produce a reduction in the number of costly dual tire failure incidents. Other developments such as greater use of x-ray, ultrasonic and holographic inspection of tire carcasses can further reduce the rate of in-service tire failures. The effect of all these improvements can alter the derived cost-justifications for tire pressure indicating systems.

There will always be times, however, when foreign object damage, wheel failure, or undiscovered internal tire structural defects will cause tire failures. Tire indicator systems, although perhaps not as cost-effective in the future for low inflation, will always be useful in reducing exposure to hazards caused by other types of failure. Each airline can thus decide on the basis of experience and future expectations which type of TPI system, if any, is suitable for its fleet.

For reasons already cited, systems able to measure actual tire pressure by analog means are favored by this study. These systems provide the most accurate means of detecting tire underinflation in any flight condition, takeoff or landing, static or in motion; the analog system allows easy

determination of whether it is operating properly and can provide through "reasonableness" checks the most effective means of eliminating false warnings; and the analog system may be used to perform daily or more frequent tire pressure checks thereby reducing maintenance costs by reducing the need for checking tire pressures by hand.

Other systems such as a weight and balance system with a blown tire detection feature are well suited for future aircraft particularly when combined with tire pressure fill valve/gauges mounted on each wheel. The fill valve/gauges can provide the ease of tire pressure checks reducing maintenance time while the weight and balance system can provide a warning of a significant tire problem after leaving the terminal. In cases where a weight and balance system is already needed, the additional hardware for a blown tire system and fill valve gauges can make a very cost-effective system, particularly if these features are built-in from the start. Again attention must be given to eliminating circuit failures which cause false warnings.

Recommendations

Throughout the study it was apparent that the exactness or thoroughness of the study of different system concepts was limited by available information on hardware that was not fully developed. Parts of the study are based on manufacturers' claims and predictions and are not backed up by actual laboratory or aircraft test data. Before a final system design or selection can be made some aircraft development testing is required. This development testing is already underway at Douglas with a preliminary design from one manufacturer for a discrete pressure sensing system. Tests of up to three advanced systems are planned for another DC-10 test aircraft late in 1978. The results of these tests will be reported in part II of this report in mid 1979. Some system design questions left unanswered in this report should be resolved by the aircraft development tests.

APPENDIX A

TIRE FAILURE AND DAMAGE COST DATA

Introduction

The intent of a tire pressure indicating (TPI) system is obviously to advise or warn of low tire pressure. With this warning the maintenance and/or flight crew can take whatever corrective action is necessary to prevent the possible consequences of an underinflated tire namely, a tire failure. With this in mind, it then becomes necessary to analyze the causes of tire failures and the consequences of those tire failures in terms of cost and increased hazard exposure.

For purposes of this study, a tire failure is herein defined as a thrown tread or a blowout. From a previous study concerning the performance of jet transport air carrier tires, it is known that the primary causes of tire failure are:

1. Foreign object damage (FOD)
2. Underinflation
3. Abuse or misuse
4. Defects in the recap procedure

By making a detailed study of the causes for aircraft tire failures for the years 1973-1976 data on damage costs to aircraft have been collected for each study aircraft. These costs were then factored to isolate those costs which might be avoided by using a TPI system.

There were various sources used to obtain the necessary data. The main sources used were the ICAO World Accident Summary, NTSB accident summary, and the FAA Service Difficulty Reports (SDR's). These sources for the years 1973-1976 provided a good summary of tire related accidents and major incidents but were poor statistical bases for failure rate and damage cost data.

To obtain better statistical tire failure data airline tire failure data was acquired. Twelve airlines were invited via letter and, in some cases, personal contact to supply tire data for the study. These airlines had been identified as good potential sources of underinflated tire failure and damage cost data. They were selected on the basis of fleet size, type of airplane in fleet (to cover all aircraft in study B-707, B-727, B-737, B-747, DC-8, DC-9, DC-10, L-1011), tire data availability and known or potential willingness to assist in the study. These airlines include domestic and European operators with fleets covering the range of study aircraft. The airline supplying the data is coded by #1, #2,

etc. For reasons of anonimity, the same airline is not always the same number in each table.

To encourage accurate analysis, several specific questions were asked to obtain similar data from all airlines. The specific information requested was:

1. The total number of tires removed due to underinflation per tire size and ply rating in the specified time period. Specific categories should be: Low or flat as a result of a wheel leak, defective tire or foreign object damage; tire failures (blowouts) for all causes; tire failures due to underinflation; thrown tread for all causes and thrown tread due to underinflation. Tire failure and thrown tread data as a direct result in underinflation is a most important source of information for this study. If exact numbers were not available, please submit your expert opinion of the number of each which were suspected to have initiated a premature removal as a result of underinflation.

2. The total number of tires by size and ply rating removed in this time period for all causes, including wear.

3. The number of incidents in which a tire failure (loss of inflation) or thrown tread resulted in airframe damage.

4. Actual repair costs for each incident in which a tire failure or thrown tread caused airframe damage. These data need not be identified by accident location or fuselage number but must be identified as to aircraft type, such as: DC-8, incident 1, incident 2, and so on. Also if aircraft delay/cancellation costs are significant, please include those, if available, but segregate them from the actual repair cost.

5. Which of the noted incidents in item 4 are positively identified or highly suspected as being caused by underinflation?

6. When do the failures that are a result of loss of tire pressure, FOD, blowouts, severe leaks, etc. occur - landing, taxi in, ramp, taxi-out, takeoff roll?

7. Are blown or leaking fuseplugs a significant cause of tire deflation?

Six excellent responses were obtained from the airlines. As anticipated, it was difficult to identify a broad data base from which to obtain well substantiated damage costs related to tire underinflation. One airline for example, provided good tire failure related damage data but was unable to differentiate between damage that may have resulted from

underinflation and other types of tire failures. Another airline believed that delay and cancellation costs should be included in the cost effectiveness study but admitted that such costs would be difficult to identify and isolate to a specific instance.

Service Difficulty Reports (SDR's) at first seemed to contain much useful information. However, after many hours of careful analysis and tabulation, the results were not particularly valuable for statistical summaries. Discrepancies were found when the tabulated results were compared to the more complete airline data. Although a few tire failure rate data points compared reasonably well most of the SDR tabulations showed tire failure rates for a particular aircraft type well below the average airline data summaries. Therefore, the tire failure study will mainly center on the airline supplied data. It is believed that since only 6 airlines submitted valuable data, it might not provide an adequate data base from which to draw broad conclusions. However, these data are expected to give indicative failure rates and damage costs that enhances the study of tire pressure indicating (TPI) systems and provides some basis for determining their cost effectiveness. The following summarizes the results.

Study Results

a. Probability of flat or low tire on a given takeoff: Before the aircraft takes off, there is a significant probability of flat or low tire due to foreign object damage, tires finally failing from carcass damage caused by underinflation, defects within the tires, etc. The following tabulation provides data for different aircraft.

In Tables A-I-A & A-I-B, the calculation was done with three of the six airlines providing useful flat and low tire data. Note that the numbers vary greatly due to an inadequate data base for each aircraft type. Each number is found based on the total number of departures and the total number of flat or low tires reported by each airline. Due to the great variance in numbers reported it was decided to total up all the number of departures and flat or low tires for all types of aircraft among the three airlines. The average comes out to be 1291. That is, the rate in which a flat or low tire occurs on a given departure is one in every 1291 departures. Note that definition of departure in this situation actually refers to when the tire is low or flat for any takeoff-landing cycle. The numbers do not include flats due to antiskid malfunctions which cause skid through tire failures. Flats or low pressure tires are normally detected at the ramp prior to departure. This data gives some idea of how often a TPI system may be called upon to provide a useful indication warning of a flat or low pressure tire.

TABLE A-I-A

SUMMARY — NUMBER OF DEPARTURES PER FLAT OR LOW TIRE (1973-1976)

AIRCRAFT / AIRLINES	DC-9	B727	B707	B747	L-1011	DC-10	DC-8	B707* B747
AIRLINE NO. 1	1095	1593	389	167	732	N/A	N/A	N/A
AIRLINE NO. 2	N/A	2395	N/A	N/A	N/A	4447	N/A	3139
AIRLINE NO. 3	3112	N/A	N/A	2466	N/A	41,263	15,647	N/A
**AVERAGE FOR ALL THREE AIRLINES	2068	2006	389	376	732	7077	15,647	3139

NOTE: 1. N/A MEANS DATA NOT AVAILABLE OR NOT SUPPLIED.
2. ALL NUMBERS ARE DEPARTURES PER FLAT OR LOW TIRE.

*ONE AIRLINE GIVES DATA ON B707 AND B747 TOGETHER BECAUSE BOTH AIRCRAFT USE THE SAME SIZE TIRE.

**AVERAGE FOR THREE AIRLINES IS COMPUTED BY THE FOLLOWING METHOD:

LET A_1 = TOTAL NUMBER OF DEPARTURES FOR AIRLINE NO. 1
A_2 = TOTAL NUMBER OF DEPARTURES FOR AIRLINE NO. 2
A_3 = TOTAL NUMBER OF DEPARTURES FOR AIRLINE NO. 3
B_1 = TOTAL NUMBER OF FLAT OR LOW TIRES FOR AIRLINE NO. 1
B_2 = TOTAL NUMBER OF FLAT OR LOW TIRES FOR AIRLINE NO. 2
B_3 = TOTAL NUMBER OF FLAT OR LOW TIRES FOR AIRLINE NO. 3

$$\text{AVERAGE} = \frac{(A_1 + A_2 + A_3)}{(B_1 + B_2 + B_3)}$$

b. Rate of incidents of tire failures causing damage: According to airline data, tire failures during takeoff can cause airframe damage even if no abort results. High damage cost is incurred if the tire failure also causes engine damage. A flat tire, will transfer its load to its mate. However, this extra load can induce a blowout of the mated tire due to overload. The highest damage costs have been incurred during dual tire failure aborts. TABLE A-II summarizes the frequency of tire failure incidents causing airframe damage. Overall average was computed taking the total number of tire failure incidents for all airlines for each aircraft type and dividing that into the total number of damage incidents per aircraft type.

Table A-II gives a good indication of the rate of incidents of tire failure causing airframe damage. By taking the average of the overall result from each aircraft, one obtains 41.4% for the entire fleet for all five airlines. From the SDR summary, it was found to be 87.5%. It's very likely that SDR data might not record the more minor tire failures while recording the major or serious incidents, thus giving a higher percentage. This is consistent with previous comments made on the statistical value of the SDR data base.

TABLE A-I-B

(1973-1976)

PROBABILITY OF FLAT OR LOW TIRE ON A GIVEN TAKEOFF

AIRLINE \ ACFT	DC-9	B727	B707	B747	L-1011	DC-10	DC-8	B707/B747*
1.	NO. DEP= 64,613 TIRES = 59 RATE = 1095 PROB = 9×10^{-2}	NO. DEP= 270,849 TIRES = 170 RATE = 1593 PROB = 6×10^{-2}	NO. DEP= 238,049 TIRES = 612 RATE = 389 PROB = 26×10^{-2}	NO. DEP= 16,685 TIRES = 100 RATE = 167 PROB = 60×10^{-2}	NO. DEP= 46,843 TIRES = 64 RATE = 732 PROB = 14×10^{-2}	N/A	N/A	N/A
2.	NO. DEP= 171,158 TIRES = 55 RATE = 3112 PROB = 3×10^{-2}	N/A	N/A	NO. DEP = 24,657 TIRES = 10 RATE = 2466 PROB = 4×10^{-2}	N/A	NO. DEP= 41,263 TIRES = 1 RATE = 41,263 PROB = 0.2×10^{-2}	NO. DEP = 125,172 TIRES = 8 RATE = 15,647 PROB = 1×10^{-2}	N/A
3.	N/A	NO. DEP = 431,088 TIRES = 180 RATE = 2395 PROB = 4×10^{-2}	N/A	N/A	N/A	NO. DEP= 57,816 TIRES = 13 RATE = 4447 PROB = 2×10^{-2}	N/A	NO. DEP = 260,567 TIRES = 83 RATE = 3139 PROB = 3×10^{-2}
**ALL THREE AIRLINES	NO. DEP= 235,771 TIRES = 114 RATE = 2068 PROB = 5×10^{-2}	NO. DEP = 701,937 TIRES = 350 RATE = 2006 PROB = 5×10^{-2}	NO. DEP = 238,049 TIRES = 612 RATE = 389 PROB = 26×10^{-2}	NO. DEP = 41,342 TIRES = 110 RATE = 376 PROB = 27×10^{-2}	NO. DEP = 46,843 TIRES = 64 RATE = 732 PROB = 14×10^{-2}	NO. DEP = 99,097 TIRES = 14 RATE = 7077 PROB = 1×10^{-2}	NO. DEP= 125,172 TIRES = 8 RATE = 15,647 PROB = 1×10^{-2}	NO. DEP= 260,567 TIRES = 83 RATE = 3139 PROB = 3×10^{-2}

DEFINITIONS
A. DEPARTURES IS DEFINED AS THE TOTAL NUMBER OF DEPARTURES OR TAKEOFFS
B. TIRES ARE THE TOTAL NUMBER OF TIRES THAT ARE FLAT OR LOW ON A GIVEN TAKEOFF
C. RATE IS THE TOTAL NUMBER OF DEPARTURES PER TIRE THAT IS FLAT OR LOW.
D. PROBABILITY REFERS TO THE TIRE THAT IS FLAT OR LOW PER DEPARTURE. THUS, HIGHER NUMBERS GIVE HIGHER PROBABILITY AND SO PROVIDE GREATER NUMBER OF FLAT OR LOW TIRES PER DEPARTURE. IT IS ALL GIVEN IN TERMS OF PERCENTAGE.

*B707 AND B747 DATA ARE COMBINED BY ONE AIRLINE SINCE THEY BOTH HAVE THE SAME TYPE OF TIRES.

**BY SUMMING THE TOTAL NUMBER OF DEPARTURES AND THE TOTAL NUMBER OF FLAT OR LOW TIRES, AN OVERALL AVERAGE WITH BETTER ACCURACY CAN BE FOUND.

TOTAL NUMBER OF DEPARTURES = 1,748,760
TOTAL NUMBER OF FLAT OR LOW TIRES = 1355
AVERAGE RATE FOR THE ENTIRE FLEET = 1291
AVERAGE PROBABILITY FOR ALL THE FLEETS = 7.8×10^{-2} PERCENT

NOTE: DUE TO THE SMALL DATA BASE THERE ARE SIGNIFICANT VARIATIONS IN RATES FROM AIRCRAFT TYPE TO AIRCRAFT TYPE WHICH DO NOT NECESSARILY AGREE WITH DAMAGE COST RATES. THEREFORE, THESE DATA ARE NOT SUITABLE FOR DRAWING COMPARATIVE CONCLUSIONS BETWEEN AIRCRAFT.

c. <u>Rate of incidents of tire failure due to underinflation</u>: The rate of incidents of tire failure including thrown treads and blowouts due to underinflation is reported in Table A-III. This is particularly difficult data to obtain since it is often difficult to determine the cause of failure after a tire has blown and the carcass largely destroyed. In some cases of thrown treads, when the tire remains inflated, a tire pressure check can reveal an underinflated condition. In cases where the pressure is normal it is often possible that the carcass was damaged some time earlier by having been run underinflated by evidence of inner liner wrinkling and other symptoms of overdeflection/underinflation.

It is important to note in this data, that in each case where the airline was able to identify underinflation as a factor in an incident, that incident involved aircraft damage. In other words, the underinflated tire failure incidents reported by the four airlines caused aircraft damage in all cases.

TABLE A-II

PERCENT TIRE FAILURE INCIDENTS CAUSING AIRFRAME DAMAGE

(1973-1976)

Airlines \ Aircraft	DC-8	DC-9	DC-10	B727	B707/B747	B747	*
Airline 1	N/A	N/A	N/A	N/A	N/A	N/A	37.7%
Airline 2	100%	90%	60%	N/A	55.6%	N/A	N/A
Airline 3	28.6%	N/A	40%	N/A	N/A	N/A	N/A
Airline 4	N/A	N/A	100%	33.3%	N/A	27.8%	N/A
Airline 5	35%	63.6%	42.9%	N/A	57.1%	N/A	N/A
Average for All 5 Airlines	37.8%	69.8%	52.6%	33.3%	56.5%	27.8%	37.7%

*Total rate for one airline without specifying the type of aircraft

TABLE A-III

PERCENT TIRE FAILURE INCIDENTS DUE TO UNDERINFLATION

(1973-1976)

Airlines \ Aircraft	DC-8	DC-9	DC-10	B747	B727	B707/B747*
Airline 1	28.6%	50%	20%	33.3%	N/A	N/A
Airline 2	20%	N/A	0%	N/A	N/A	N/A
Airline 3	N/A	N/A	100%	N/A	33.3%	27.8%
Airline 4	30%	33.3%	14.3%	7.14%	N/A	N/A
Total Average for All Airlines**	25.6%	37.2%	21.1%	17.4%	33.3%	27.8%

*Due to the tire size being the same, this particular airline grouped both B707 and B747 together

**Average for all aircraft types is 27.2%

As found in Table A-II, the percentage of tire failure incidents that caused aircraft damage and contributed to aircraft damage cost is 41.4% (or 41.4 out of 100 incidents). Per Table A-III, 27.2% of tire failures are caused by underinflation, but all of the 27.2% caused aircraft damage. So the percentage of damage cost due to underinflation is 27.2%/41.4% x 100 = 65.7%. So 65.7% of the damage cost can be attributed to underinflation related tire failures. If we assume that a tire pressure indicating system will provide early warning of this underinflation condition, then a good TPI system might save 65.7% of the aircraft damage cost incurred on any given aircraft type by tire failures. This is the figure then used in the cost-effectiveness study.

d. Actual damage cost per departure: Several airline's data does include a thorough damage cost estimate for each aircraft. It appears that the data is biased to the major incidents. A minor incident which inputs a small amount of damage cost is often not recorded. Because of this some respondents consider the damage costs reported to be conservative. The following table gives the damage cost tabulation for the 1973-1976 time period.

The damage costs reported in Table A-IV-A are as accurate as possible with two exceptions. There was one incident for the B-747 and one for the DC-10 in which damage costs were so high that the overall damage costs per departure would have increased from $0.72 to over $2.00; the per departure cost for the B-747 would have been over $13.00; over $9.00 for the DC-10. With the small data base, these incidents were overwhelming in their influence and it was decided to eliminate them to be conservative in the cost-effectiveness study. It should be noted, however, that the major incidents provide the clearest indication of a need for a cockpit indicating tire pressure system since in these cases, early warning of tire problems may have substantially reduced aircraft damage. A more detailed tire failure related damage cost calculation is shown in Table A-IV-B.

It is also worthy of note that no or little data was obtained on the L-1011 for this study. There is evidence in the incident summary that the L-1011 has experienced tire failures with attendant aircraft damage but no information was obtained from any of the twelve airlines campaigned.

TABLE A-IV-A

AIRLINE AIRCRAFT DAMAGE COSTS CAUSED BY TIRE FAILURE
(1973-1976)

AIRLINES \ AIRPLANES	DC-8	DC-9	DC-10	B707	B727	B737	B747
AIRLINE NO. 1	N/A	N/A	$14,735	$91,560	$66,068	$141,605	$272,832
AIRLINE NO. 2	N/A	N/A	$522,269	0	$30,253	N/A	$18,284
AIRLINE NO. 3	$13,830	$79,310	0	N/A	N/A	N/A	$110
AIRLINE NO. 4	$168,130	$54,930	$39,980	N/A	N/A	N/A	$59,360
TOTAL FOR 4 AIRLINES	$181,960	$134,240	$576,984	$91,560	$96,321	$141,605	$350,586
NO. OF DEPARTURES	158,485	373,240	147,959	334,270	783,060	323,616	68,555
DAMAGE COST PER DEPARTURE	$1.15	$0.36	$3.90	$0.27	$0.12	$0.44	$5.11

TABLE A-IV-B

DAMAGE COST PER DEPARTURE 1973-1976

AIRLINE \ ACFT	B707	B727	B737	B747	DC-8	DC-9	DC-10
1.	DAM. COST = $91,560 DEP = 88,044 RATE = $1.04	DAM. COST = $66,068 DEP = 351,972 RATE = $0.19	DAM. COST = $141,605 DEP = 323,616 RATE = $0.44	DAM. COST = $272,832 DEP = 23,760 RATE = $11.48	N/A	N/A	DAM. COST = $14,735 DEP = 24,924 RATE = $0.59
2.	DAM. COST = $0 DEP = 246,226 RATE = $0	DAM. COST = $30,253 DEP = 431,088 RATE = $0.07	N/A	DAM. COST = $18,284 DEP = 14,341 RATE = $1.27	N/A	N/A	DAM. COST = $522,269 DEP = 57,816 RATE = $9.03
3.	N/A	N/A	N/A	DAM. COST = $110 DEP = 5797 RATE = $0.02	DAM. COST = $13,830 DEP = 33,313 RATE = $0.42	DAM. COST = $79,310 DEP = 201,932 RATE = $0.39	DAM. COST = $0 DEP = 23,956 RATE = $0
4.	N/A	N/A	N/A	DAM COST = $59,360 DEP = 24,657 RATE = $2.41	DAM. COST = 168,130 DEP = 125,172 RATE = $1.34	DAM. COST = $54,930 DEP = 171,158 RATE = $0.32	DAM. COST = $39,980 DEP = 41,263 RATE = $0.97
*	DAM. COST = $91,560 DEP = 334,270 RATE = $0.27	DAM. COST = $96,321 DEP = 783,060 RATE = $0.12	DAM. COST = $141,605 DEP = 323,616 RATE = $0.44	DAM. COST = $350,586 DEP = 68,555 RATE = $5.11	DAM. COST = $181,960 DEP = 158,485 RATE = $1.15	DAM. COST = $134,240 DEP = 373,090 RATE = $0.36	DAM. COST = $576,984 DEP = 147,959 RATE = $3.90

*SUMMING THE TOTAL DAMAGE COST AND DEPARTURES FOR EACH TYPE OF AIRCRAFT, RATE OF DAMAGE COST PER DEPARTURE CAN BE FOUND FOR EACH TYPE AIRCRAFT.

FOR THE ENTIRE FLEET OF AIRCRAFT, THAT IS, WHEN ALL TYPES OF AIRCRAFT FROM EACH AIRLINE ARE ADDED TOGETHER, THE AVERAGE RATE OF DAMAGE COST PER DEPARTURE WILL BE:

TOTAL AMOUNT OF DAMAGE COST = $1,573,256

TOTAL DEPARTURES = 2,189,035

∴ RATE OF DAMAGE COST PER DEPARTURE = **$0.72**

e. Actual delay and cancellation costs per departure: Insufficient data were received on this topic. As pointed out earlier, such delay and cancellation costs are difficult to identify and isolate to a specific incident. Only one airline had such data available. One other airline provided the delay time in hours which did not help in arriving at a result. Thus these costs were based on the only available airline data. In covering the years through 1973-1976, the actual delay and cancellation costs per departure for the DC-8 was $1.48, for the DC-9 it was $0.07, for the DC-10 it was $6.54, and for the B-747 it was $22.14. By totaling the cost for all the aircraft an average of $2.79 is obtained. This refers to the cost which resulted from delay and cancellations because of tire failures.

f. Costs of tire scrappage: A preliminary evaluation of the costs that may be avoided by reducing the scrap rate of carcasses due to underinflation related damage appear to be relatively insignificant. According to data from several sources, the scrap rate of tires for wrinkled inner liners (an indication that tire has been run underinflated) varies between 1% and 5% of aircraft tire rejections. Looking at the cost of a 737 or DC-10 tire at $460 and $850 respectively and the cost of a recap at $140 and $160 and assuming four retreads and 200 landings per tread or a carcass life of 1000 landings, this gives a cost per tire landing of approximately $1.00 and $1.50 respectively. If a tire pressure indicating (TPI) system could prevent all the tire scrappage at the maximum 5% rate, this would save $0.05 per landing on a 737 and $0.075 per landing for a DC-10. This cost, compared to a $0.72 per landing airframe damage cost, makes tire scrappage costs an insignificant portion of total costs. It is therefore, not included in the cost-effectiveness study.

Summary of Damage and Delay Costs

The final analysis of the damage cost provides interesting results. The aircraft related damage cost from tire failures varies between $0.12 per departure to over $5.00 with an average of $0.72 per departure. The lower dollar figures primarily come from narrow body aircraft with the wide body aircraft producing the higher cost per departure. Statistically the narrow body aircraft have as many or more tire failures, but the cost per incident is often substantially higher for the wide body aircraft.

The airframe damage cost per incident ranged from $3,000 to $50,000 as reported by airlines. One respondent not included in the above study reported average damage costs per tire failure incident of $40,000. The cost per incident can vary widely, however, since a significant number of relatively low cost incidents, plus one or two incidents that cost from $200,000 to $3,000,000 can occur. For example, one airline

reported 61 tire related damage work orders costing $185,351 or an average of slightly over $3,000 per incident for one year, but then cited one B-747 incident in that year which exceeded the cost of the total of 61 other incidents. In another case an airline reported a DC-10 incident costing over $2.6 million, primarily due to engine damage occurring during the abort, as the only incident on their wide body fleet in that year. This one incident caused the damage cost per landing to be over $100 for that airline's fleet for that year.

It is also clear, as should be expected, that delay and cancellation costs vary as a function of aircraft size, age and other fixed costs. The data base for these costs is inadequate to include this parameter in the cost-effectiveness study directly, but it should not be ignored as insignificant. Delay and cancellation costs would appear to exceed damage costs in certain tire failure incidents.

g. <u>Accident and Incident Summary</u>

To obtain a clearer picture of the number and type of accidents and incidents that an early warning of low inflation pressure may have helped to avoid, a thorough study of accidents and incidents was conducted using the ICAO World Accident Summary, NTSB Accident Report, and other sources. Some of the accidents and incidents which may have been avoided with an early warning cockpit TPI system are described below:

Incident - May 1978

L-1011 during takeoff from Charles De Gaulle Airport, had number 8 tire (4R) blow-out at 70 kts. Takeoff aborted at 110 kts. Gross weight approximately 390,000 lbs. Three other tires on right gear blew before or during abort. Extensive aircraft damage resulted including ingestion of wheel and tire debris into #3 engine. Uncertain whether failure was caused by wheel flange failure or tire failure. Similar incident at Bahrain several days later involved front two wheels on left gear. TPI system would have provided solid indication at 70 kts possibly earlier so that abort may have been initiated earlier reducing damage.

Incident - 12 April 1978

DC-10-30 during takeoff from Reef runway at Honolulu International Airport at 552,700 lbs. At least one tire reportedly blew at 160 kts. Takeoff aborted at 176 kts IAS, 9 kts over V1. Tires 3, 4, 5, 6, 7, 8 flat at stop in overrun area. Investigation revealed tire #4 apparently started to go flat prior to turning on runway. #3 tire failed due to overload at 160 kts. Other tires failed during

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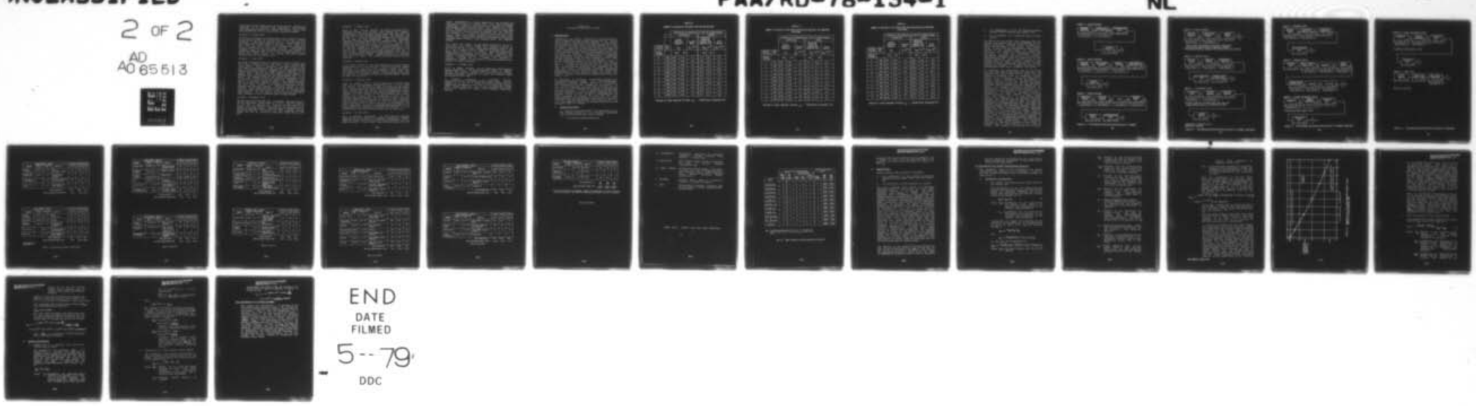

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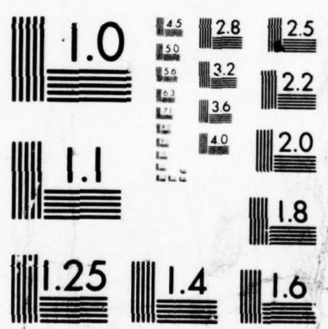


MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

abort due to wheel debris from #3 and #4 wheels. Damage cost estimated to be $253,000 plus some parts. This incident could have been avoided by a cockpit TPI system which would have allowed the crew to stop before taking the runway.

Accident - 1 March 1978

DC-10-10 at Los Angeles International Airport aborted takeoff at max gross weight of 430,000 lbs at V1 due to tire failures. Crew report bang at 154 kts. Aborted takeoff on wet runway and overran runway by 670 feet. Left hand gear with only one tire intact broke through soft macadam and failed. Resulting fire destroyed aircraft. Investigation revealed tires #1 and #2 failed initially with evidence of overheated sidewall above bead. There is disagreement as to which tire failed first. TPI system may have provided warning early in the takeoff roll.

Incident - 7 June 1976

DC-10-30 Kinshasa during the takeoff run, about 1,200 m from the runway threshold, one of the main right landing gear tires burst. Shortly thereafter, the second tire of that twin wheel disintegrated and the aircraft kept rolling on the rims of the front wheels. Fragments of the rims were thrown forward and sucked into the right engine resulting in an engine fire. When the pilot-in-command saw the engine fire warning light he activated the fire extinguisher, but to no avail. He decided to abort the takeoff and managed to stop the aircraft 1,000 m before the runway end. Evacuation took place in an orderly manner by means of the emergency chutes and the airport fire fighting services efficiently brought the fire under control. The engine was destroyed and the airframe was seriously damaged. Estimated damage at $2.6 million. Some suspicion that #3 tire failure may have been caused by taxi light and #4 tire failed due to overpressure plug failure. A TPI system may have provided sufficient early warning to have avoided the major engine damage.

Accident - 25 August 1975

DC-10-10 at JFK at 401,000 lbs. On takeoff crew heard pop at 80 kts, additional "pops" heard at 145 kts. Takeoff aborted at 154 kts, 6 kts over V1. Aircraft overran runway by 50 yards. All tires failed on left gear two on right gear flat. Extensive aircraft damage. Rough estimate of damage cost was placed at $500,000. TPI system may have provided warning before 80 kts but should at least have caused abort at 80 kts.

Incident - 2 August 1974

DC-8 at LAX. During takeoff the pilot-in-command felt a vibration through the aircraft and aborted the takeoff. Subsequently he was advised by the tower that there was fire in the area of the left main landing gear. The aircraft was brought to a stop on taxiway 28J adjacent to security post No. 2, and the fire department. The fire department responded and extinguished the fire expeditiously. The total takeoff run distance was 1,450 m (9/10 mi). Debris, tire rubber and wheel rim were found for a total distance of 1,120 m (7/10 mi). Evidence on taxiway J revealed that No. 6 tire on the left landing gear was flat prior to initiation of the takeoff roll. Evidence on the runway indicated that No. 5 tire failed during takeoff run approximately 145 m (475 ft) from the displaced threshold. Damage estimated at $163,000 less cost of gear. TPI system could have prevented this incident.

Incident - October 1974

B-747 during takeoff at Tokyo experienced tire failures which caused abort at or near rotation. Extensive aircraft damage resulted. #11 and #12 tires failed causing the abort. Investigation revealed that an excessively tight taxi turn may have caused failure of wheel. Load leveling system also in question. A TPI system could have detected wheel failure as early as taxi turn.

Accident - 6 December 1975

B-747 at Bombay, India. While aligning for takeoff during 180° turn at the beginning of Runway 27, No. 11 tire blew out/ failed. No. 12 tire also blew out/failed during takeoff run. Following blowing out of tires on starboard body gear, truck tilted and the wheels and brake assemblies started rubbing the runway surface, generating excessive heat which, coupled with hot brakes on 9 and 10 wheels due to overloading and braking action, originated a fire in the starboard body gear wheels. Due to initial delay in shutting down the engines which hampered the effective fire fighting, coupled with certain amount of lack of coordination and proper deployment of the fire fighting men and equipment, the fire originally confined to starboard body gear grew into a conflagration and ultimately destroyed the aircraft. A TPI system would have detected the failure at the taxi turn.

Incident - 22 June 1973

DC-9 at Spokane, Washington. At 2156 hours the aircraft began takeoff from runway 21 at Spokane, Washington. Takeoff appeared normal until the aircraft had accelerated to 131 kt about midfield. At this time a loud noise was heard from the

right, accompanied by severe vibration of the aircraft and fluctuation of the No. 2 engine EPR's. The pilot-in-command immediately called for rejected takeoff, applied full brakes and emergency power reverse thrust, and extended the wing slats. Vibration of the aircraft increased as it slowed down but directional control was not a problem and the aircraft was brought to a stop 60 m (200 ft) before the end of the runway. Tower controllers, observing fire on the right main landing gear tires during takeoff, dispatched fire fighting equipment which arrived a few minutes after the airplane halted.

Tire marks and debris on the runway showed that the No. 4 tire blew out at 1,460 m (4,800 ft), followed closely by blowout of the No. 3 tire. Other marks showed blowout of the No. 1 and 2 tires at 2,070 m (6,800 ft) following solid skid marks 240 m (800 ft) in length. When the wheels were disassembled the bearings were found well lubricated and capable of normal operation. There was no evidence of brake failure. Although the No. 2 engine had ingested a substantial amount of tire rubber, it was checked and found capable of normal operation.

Incident - 4 January 1974

B-727 at Tampa, Florida. Tire on right gear disintegrated during takeoff roll. #3 engine ingested pieces of rubber. Takeoff was aborted. During abort a fire started in brakes and wheel assembly spreading to wheel well before being extinguished (NTSB 4495).

In another tabulation of tire/wheel failure incidents/accidents involving overruns and/or major aircraft damage, in 6 out of 9 cases the initial failure was not immediately recognized by the crew. It is these high damage costs, highly hazardous tire failure incidents which give much of the impetus to cockpit tire pressure indicating systems.

APPENDIX B
RELIABILITY AND SAFETY STUDIES

I. INTRODUCTION

Reliability and safety analyses have been performed to compare eleven different design concepts for the cockpit Tire Pressure Indicating (TPI) Systems. So application on different aircraft can be compared, results are given in Table B-I for each concept on aircraft with 6, 10, and 18 wheels. Equations to calculate the five pertinent TPI system reliabilty and safety parameters shown in Table B-I are provided together with an explanation of each term following the equation. Standard reliability symbology and nomenclature are used. The exponential probability density function model (constant failure rate with time) is used throughout, that is the reliability, R, of a system operating properly for a given period of time, t, is $R = e^{-\lambda t}$, when λ is the failure rate for the failure mode of interest in failures per unit of operating time and t is the exposure to failure time expressed in the same time units. Conventional binominal probability mathematics are used to calculate joint and conditional probabilities of the specific events of interest. The symbol Q is used to designate the probability of failure, thus $Q = 1-R$.

In additiion, an important relationship between Mean-Time-Between-Failures (MTBF), and Mean-Time-Between-Unscheduled Removals (MTBUR) appears in the analysis. This relationship is MTBF = (MTBUR) (K) (Z), where K is the ratio of component operating time to flight time and Z is the ratio of component line removals to subsequently verified failures. K and Z result from the fact that certain equipment is often operated or energized when the aircraft is not, i.e. at the ramp or in maintenance, and often equipment is removed in error due to poor troubleshooting and subsequently tests good on the bench. A typical value for the product of the factors K and Z is 1.5. This has been used in the analyses resulting in the expression MTBF = 1.5 MTBUR.

A. Reliability Study

To evaluate the reliability of the estimates of the TPI system, estimates of the following parameters were calculated for each system concept:

1. The Mean-Time-Between-Failures.

TABLE B-I

SUMMARY OF RELIABILITY AND SAFETY DATA AND CALCULATIONS

		Probability Per Departure for Each TPI System Concept					
		Reliability			Safety		
		System Operating Properly		Dispatch Delay	System Not Operating Properly With Low/Flat Tire		False Warning
10-Wheel Aircraft	MTBF (Hr)	R_{TPI}		Q_D (10^{-4})	Q_{HAZ} (10^{-5})		Q_{FW} (10^{-7})
Concept (System)		3%*	0%*		3%*	0%*	
D	810	0.82	0.99	4.7	4.3	0.2	0.5
E	750	0.66	0.98	5.0	8.2	0.5	2.2
F	615	0.60	0.98	5.0	9.6	0.5	2.7
G	518	0.07	0.91	7.8	22.4	2.2	11.2
H	3279	0.57	0.90	1.6	10.4	2.4	3.8
I	1724	0.46	0.92	2.9	13.0	1.9	1.9
J	1785	0.39	0.90	2.5	14.7	2.4	7.0
K	620	0.90	0.90	5.4	21.9	2.4	20.1
L	760	0.26	0.93	6.0	17.8	1.7	5.5
M	662	0.21	0.93	6.7	19.0	1.7	6.3
N	610	0.25	0.95	7.2	18.1	1.2	6.8

*Percent of "never detected" failures, t_{op} = 100,000 hours (Paragraph IIA).

TABLE B-I

SUMMARY OF RELIABILITY AND SAFETY DATA AND CALCULATIONS PER DEPARTURE (Continued)

		Probability Per Departure for Each TPI System Concept					
		Reliability			Safety		
		System Operating Properly		Dispatch Delay	System Not Operating Properly with Low/Flat Tire		False Warning
6-Wheel Aircraft	MTBF (Hr)	R_{TPI}		Q_D (10^{-4})	Q_{HAZ} (10^{-5})		Q_{FW} (10^{-7})
Concept (System)		3%*	0%*		3%*	0%*	
D	1161	0.87	0.99	3.5	0.6	0.05	0.4
E	1085	0.74	0.98	3.7	1.3	0.1	1.5
F	907	0.70	0.98	4.2	1.5	0.1	1.8
G	855	0.20	0.91	5.6	3.9	0.4	6.8
H	4082	0.62	0.90	1.1	1.8	0.5	3.1
I	2674	0.59	0.92	2.3	2.0	0.4	1.3
J	2841	0.53	0.90	1.9	2.3	0.5	4.4
K	1031	0.21	0.90	3.6	3.8	0.5	12.1
L	1205	0.41	0.93	4.7	2.9	0.03	3.5
M	971	0.33	0.93	5.3	3.2	0.3	4.3
N	1000	0.43	0.95	5.3	2.8	0.2	4.2

*Percent of "never detected" failures, t_{op} = 100,000 hours (Paragraph IIA).

TABLE B-I

SUMMARY OF RELIABILITY AND SAFETY DATA AND CALCULATIONS PER DEPARTURE (Continued)

18-Wheel Aircraft	MTBF (Hr)	Probability Per Departure for Each TPI System Concept: Reliability — System Operating Properly R_{TPI}		Reliability — Dispatch Delay Q_D (10^{-4})	Safety — System Not Operating Properly With Low/Flat Tire Q_{HAZ} (10^{-5})		Safety — False Warning Q_{FW} (10^{-7})
Concept (System)		3%*	0%*		3%*	0%*	
D	509	0.74	0.98	7.2	20.9	0.8	0.8
E	466	0.51	0.98	7.6	39.3	1.6	3.6
F	372	0.44	0.98	9.3	45.0	1.6	4.5
G	290	0.01	0.91	12.2	79.5	7.2	20.1
H	2353	0.48	0.90	1.1	41.8	8.0	5.3
I	978	0.27	0.92	4.2	58.6	6.4	3.4
J	1025	0.21	0.90	3.6	63.4	8.0	12.2
K	346	0.01	0.90	9.0	79.5	8.0	36.1
L	441	0.10	0.93	9.0	72.3	5.6	9.5
M	405	0.08	0.93	9.6	73.9	5.6	10.3
N	242	0.09	0.95	11.1	73.1	4.0	12.2

*Percent of "never detected" failures, t_{op} = 100,000 hours (Paragraph IIA).

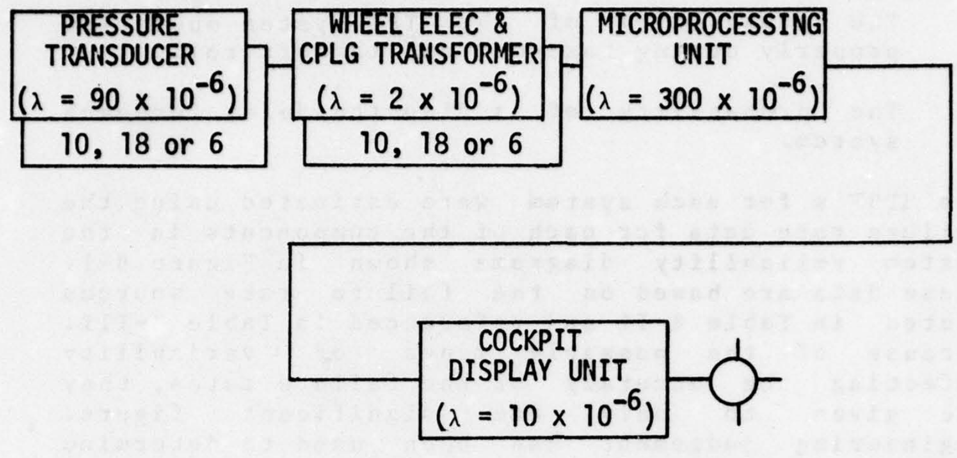
2. The probability of the TPI system operating properly during taxi-out and takeoff roll.

3. The probability of a dispatch delay for each system.

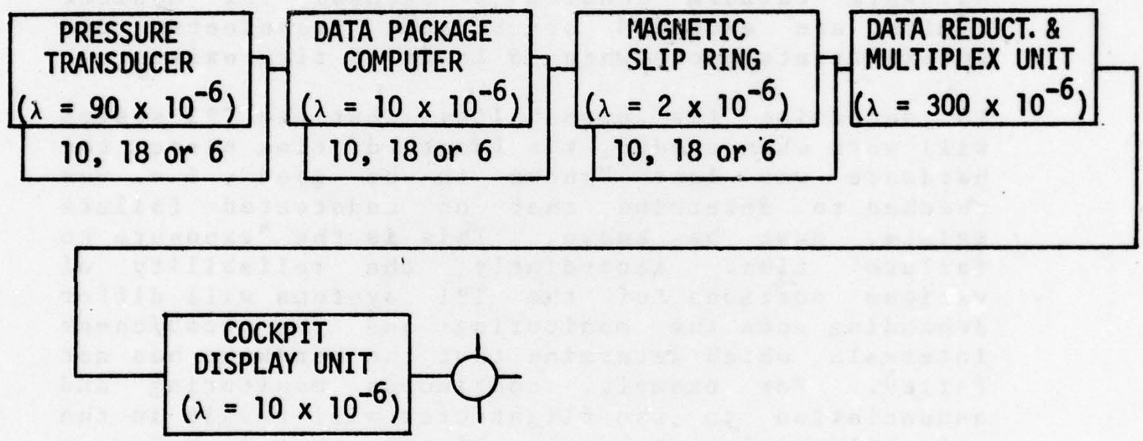
The MTBF's for each system were estimated using the failure rate data for each of the components in the system reliability diagrams shown in Figure B-1. These data are based on the failure rate sources stated in Table B-II and referenced in Table B-III. Because of the possible range of variability affecting the accuracy of the failure rates, they are given to only one significant figure. Engineering judgement has been used to determine representative values, shown in Tablle B-IV, of the percent monitoring within each TPI system and the probabilities of false warnings caused by non-hardware failure conditions because TPI monitor limits are exceeded or because transients and intermittents occur when no low/flat tire exists.

To determine the probability that the TPI system will work when needed, the length of time since the hardware was last "known to be good", i.e. was checked to determine that no undetected failure exists, must be known. This is the "exposure to failure" time. Accordingly, the reliability of various portions of the TPI systems will differ depending upon the monitoring and the test/check intervals which determine that the hardware has not failed. For example, continuous monitoring and annunciation to the flight crew will result in the reliability of that portion of the system being a function of the length of operating time under consideration, i.e. from power-on through takeoff roll, per flight, etc. In this study, these failures are referred to as detected failures. Failures that are not detected when they occur but rather when a specific test or check is made are referred to as undetected failures. The undetected failures include the hardware failures that are discovered either during a Built-In-Test Equipment (BITE) test which is conducted when equipment suspected of a malfunction is removed from an aircraft, or during an Acceptance Test Procedure (ATP) which is conducted after failed equipment is repaired. The corresponding average exposure to failure times for these undetected failures are the MTBUR and MTBF, respectively. One additional category of undetected failures exists, that is, failures that are not detected by any tests or checks. Such failures are referred to as "never"

CONCEPT D - ANALOG PRESSURE



CONCEPT E - ANALOG PRESSURE



CONCEPT F - ANALOG PRESSURE

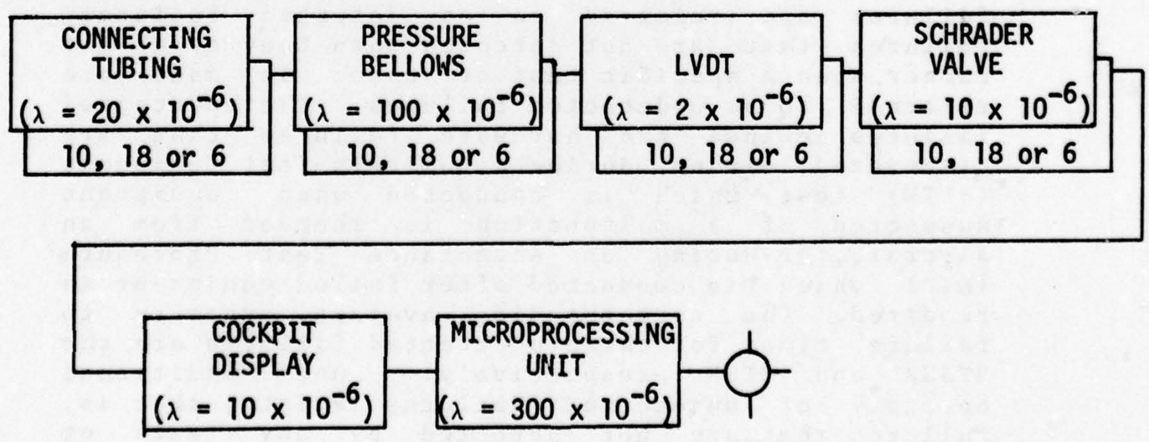
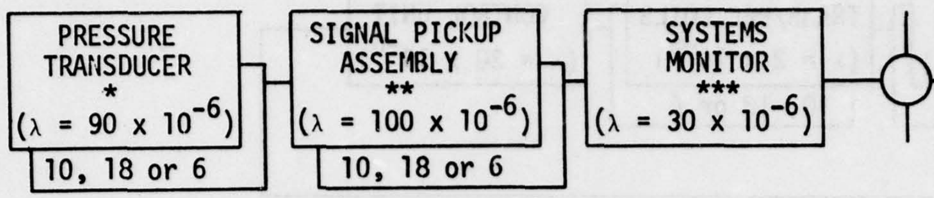


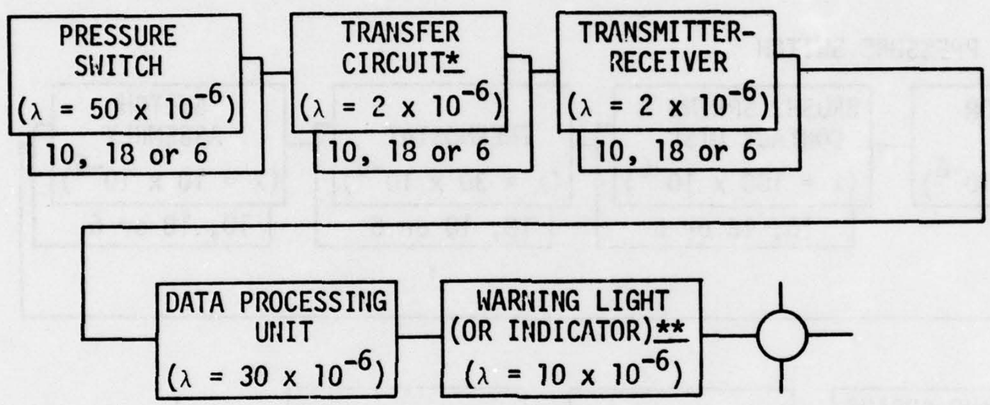
FIGURE B-1. TIRE-PRESSURE-INDICATING-SYSTEM RELIABILITY DIAGRAMS

CONCEPT G - ANALOG PRESSURE

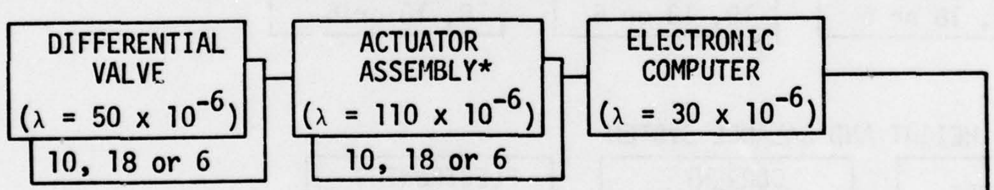


*Solid state, temperature and pressure compensated.
**Electromechanical through a commutator assembly.
***Displays tire/wheel condition with audio and visual warning.

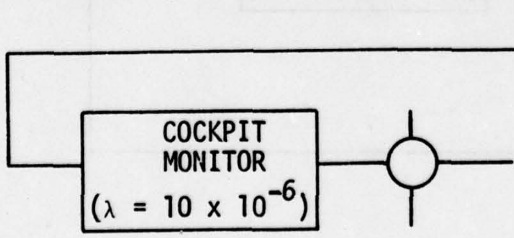
CONCEPT H - PRESSURE SWITCH



CONCEPT I - DIFFERENTIAL VALVE



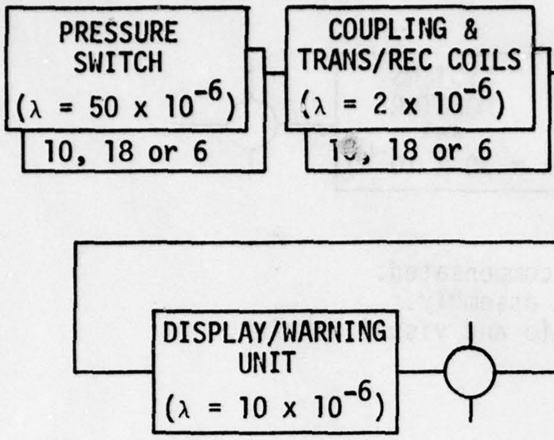
*Includes pressure transducer axle slip rings and interconnecting tube to a differential valve.



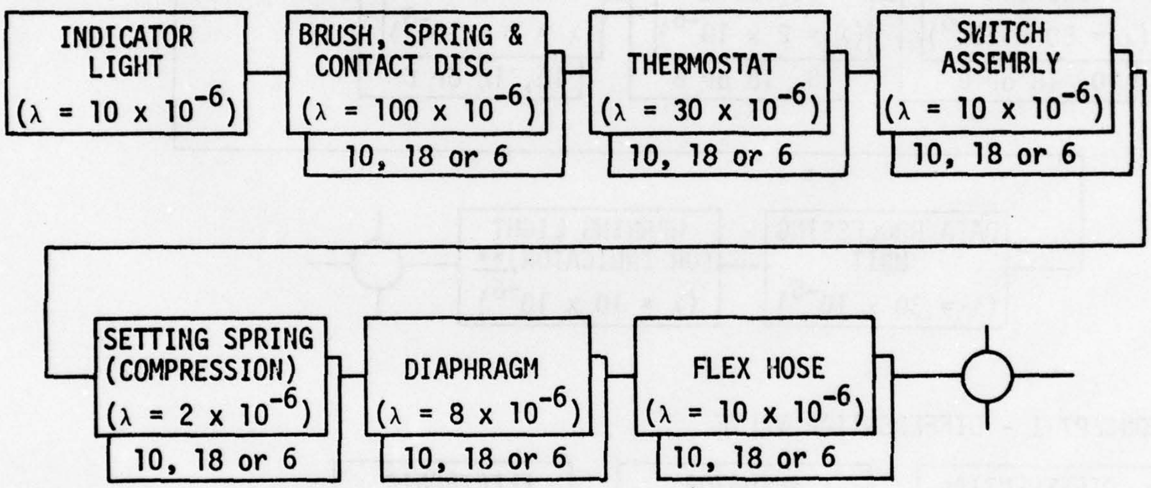
*Consists of inductive coils.
**Indicator optional.

FIGURE B-1. TIRE-PRESSURE-INDICATING-SYSTEM RELIABILITY DIAGRAMS (CONTINUED)

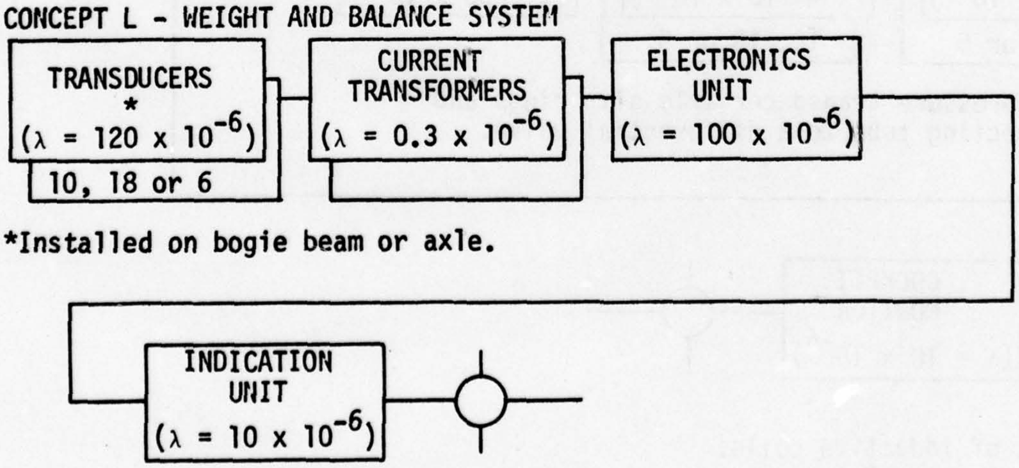
CONCEPT J - PRESSURE SWITCH



CONCEPT K - PRESSURE SWITCH



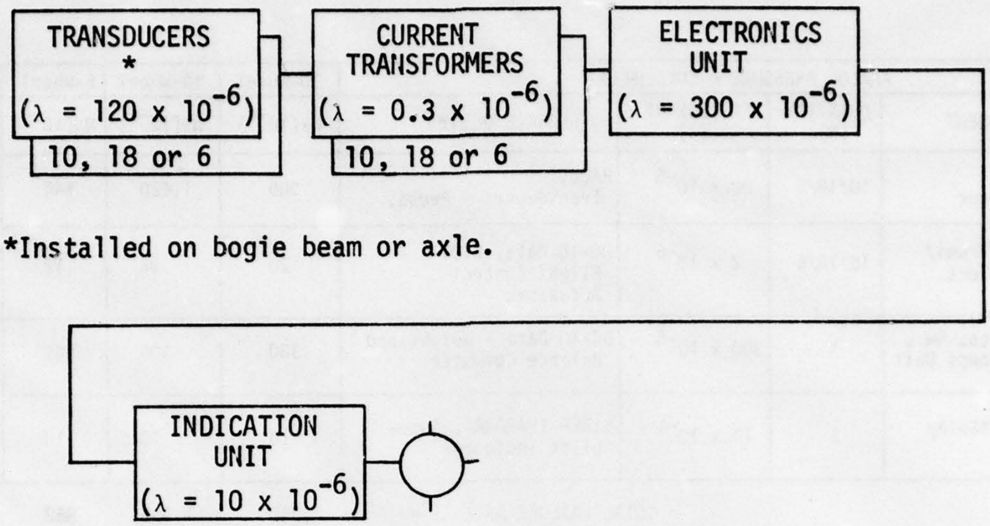
CONCEPT L - WEIGHT AND BALANCE SYSTEM



*Installed on bogie beam or axle.

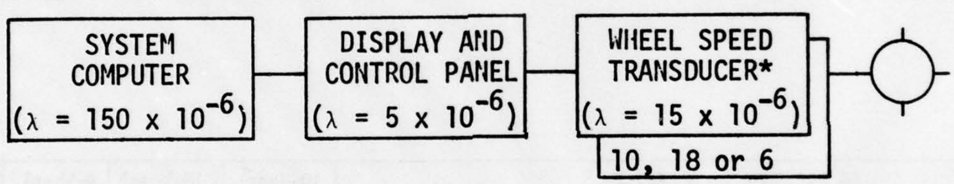
FIGURE B-1. TIRE-PRESSURE-INDICATING-SYSTEM RELIABILITY DIAGRAMS (CONTINUED)

CONCEPT M - WEIGHT AND BALANCE SYSTEM



*Installed on bogie beam or axle.

CONCEPT N - WHEEL SPEED



*Exists on aircraft.

FIGURE B-1. TIRE-PRESSURE-INDICATING-SYSTEM RELIABILITY (CONTINUED)

ANALOG PRESSURE — CONCEPT D				10-Wheel	18-Wheel	6-Wheel
COMPONENT	QUANTITY (N)	FAILURE RATE (λ)	SOURCE OF λ*	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$
Pressure Transducer	10/18/6	90×10^{-6}	RADC, Transducers - Press.	900	1,620	540
Coupling Trans/ Wheel Elect.	10/18/6	2×10^{-6}	DC-10 Data, LVDT-Flight Control Actuators	20	36	12
Electronics, Sw., & M/Process Unit	1	300×10^{-6}	DC-10 Data - Weight and Balance Computer	300	300	300
Cockpit Display Unit	1	10×10^{-6}	GIDEP (FARADA), Auto-pilot Indicator	10	10	10
			TOTAL FAILURE RATE: λ =	1,230	1,966	862
			MEAN TIME BETWEEN FAILURES: MTBF** =	813 hr	509 hr	1,160 hr

ANALOG PRESSURE — CONCEPT E				10-Wheel	18-Wheel	6-Wheel
COMPONENT	QUANTITY (N)	FAILURE RATE (λ)	SOURCE OF λ	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$
Pressure Transducer	10/18/6	90×10^{-6}	RADC, Press. Xdcr.	900	1,620	540
Data Package	10/18/6	10×10^{-6}	Estimate	100	180	60
Magnetic Slip Ring	10/18/6	2×10^{-6}	DC-10 Data, LVDT - Flight Control Actuators	20	36	12
Multiplex Unit	1	300×10^{-6}	DC-10 Data, Weight and Balance Computer	300	300	300
Display Unit	1	10×10^{-6}	GIDEP (FARADA), Auto-pilot Indicator	10	10	10
			TOTAL FAILURE RATE: λ =	1,330	2,146	922
			MEAN TIME BETWEEN FAILURES: MTBF =	752 hr	466 hr	1,085 hr

*See Table B-III
**Where MTBF = $1/\lambda$

TABLE B-II. FAILURE RATE DATA FOR EACH TPI SYSTEM CONCEPT

ANALOG PRESSURE — CONCEPT F				10-Wheel	18-Wheel	6-Wheel
COMPONENT	QUANTITY (N)	FAILURE RATE (λ)	SOURCE OF λ	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$
Schrader Valve	10/18/6	10×10^{-6}	RADC, Check Valves, Pneumatic System	100	180	60
Connecting Tubing	10/18/6	20×10^{-6}	FARADA, C1 #1658S	200	360	120
Pressure Bellows	10/18/6	100×10^{-6}	RADC, Bellows,	1,000	1,800	600
LVDT	10/18/6	2×10^{-6}	DC-10 Data, Flight Control Alt.	20	36	12
Cockpit Display	1	10×10^{-6}	GIDEP (FARADA), Auto-pilot Indicator	10	10	10
Electronics, Sw., & M/Process Unit	1	300×10^{-6}	DC-10 Data - Weight and Balance Computer	300	300	300
			TOTAL FAILURE RATE: λ =	1,630	2,686	1,102
			MEAN TIME BETWEEN FAILURES: MTBF =	614 hr	372 hr	907 hr

ANALOG PRESSURE — CONCEPT G				10-Wheel	18-Wheel	6-Wheel
COMPONENT	QUANTITY (N)	FAILURE RATE (λ)	SOURCE OF λ	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$
Pressure Transducer	10/18/6	90×10^{-6}	RADC, Transducers - Pressure	900	1,620	540
Signal Pick-up Assembly	10/18/6	100×10^{-6}	RADC, Slip Ring Assy, Helicopter ($200 \times 10^{-6} \times 1/2$ for Aircraft)	1,000	1,800	600
Systems Monitor & Indicator	1	30×10^{-6}	DC-10 Data - Brake Temperature Monitor Computer	30	30	30
			TOTAL FAILURE RATE: λ =	1,930	3,450	1,170
			MEAN TIME BETWEEN FAILURES: MTBF	518 hr	290 hr	855 hr

TABLE B-II (Continued)

PRESSURE SWITCH — CONCEPT H				10-Wheel	18-Wheel	6-Wheel
COMPONENT	QUANTITY (N)	FAILURE RATE (λ)	SOURCE OF λ	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$
Pressure Switch	10/18/6	50×10^{-6}	RADC, Pressure Switch	500	900	300
Transfer Circuit (Inductive Coils)	10/18/6	2×10^{-6}	DC-10 Data - LVDT, Flight Control Actuators	20	36	12
Transmitter-Receiver Circuit	10/18/6	2×10^{-6}	DC-10 Data - LVDT, Flight Control Actuators	20	30	12
Data Processing Unit	1	30×10^{-6}	DC-10 Data - Brake Temperature Monitor Computer	30	10	30
Warning Light (or Indicator)	1	10×10^{-6}	GIDEP (FARADA), Takeoff Warning System	10	10	10

TOTAL FAILURE RATE: λ = 580 1,022 374

MEAN TIME BETWEEN FAILURES: MTBF = 1,724 hr 978 hr 2,674 hr

DIFFERENTIAL VALVE — CONCEPT I				10-Wheel	18-Wheel	6-Wheel
COMPONENT	QUANTITY (N)	FAILURE RATE (λ)	SOURCE OF λ	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$
Actuator Assembly	10/18/6	110×10^{-6}	Transducer — RADC, Slip Ring — DC-10 Data (LVDT), Tubing — GIDEP (FARADA)	1,100	1,980	660
Differential Valve	10/18/6	50×10^{-6}	RADC, Pressure Switch	500	900	300
Electronic Computer	1	30×10^{-6}	DC-10 Data - Weight and Balance Computer	30	30	30
Cockpit Monitor	1	10×10^{-6}	GIDEP (FARADA) Autopilot Indicator	10	10	10

TOTAL FAILURE RATE: λ = 1,640 2,920 1,000

MEAN TIME BETWEEN FAILURES: MTBF = 610 hr 342 hr 1,000 hr

TABLE B—II (Continued)

PRESSURE SWITCH — CONCEPT J				10-Wheel	18-Wheel	6-Wheel
COMPONENT	QUANTITY (N)	FAILURE RATE (λ)	SOURCE OF λ	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$
Pressure Switch	10/18/6	50×10^{-6}	RADC, Pressure Switch	500	900	300
Coupling/Trans-Receiver Coils	10/18/6	2×10^{-6}	DC-10 Data — LVDT Flight Control Actuators	20	36	12
Electronic Control Unit	1	30×10^{-6}	DC-10 Data — Brake Temperature Monitor Computer	30	30	30
Warning Unit	1	10×10^{-6}	GIDEP (FARADA), Autopilot Indicator	10	10	10

TOTAL FAILURE RATE: λ = 560 976 352

MEAN TIME BETWEEN FAILURES: MTBF = 1,786 hr 1,025 hr 2,841 hr

PRESSURE SWITCH — CONCEPT K				10-Wheel	18-Wheel	6-Wheel
COMPONENT	QUANTITY (N)	FAILURE RATE (λ)	SOURCE OF λ	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$
Indicator Light	1	10×10^{-6}	GIDEP (FARADA), Takeoff Warning System	10	10	10
Brush, Spring & Contact Disk	10/18/6	100×10^{-6}	RADC, Slip Ring Assembly, Helicopter	1,000	1,800	600
Thermostat	10/18/6	30×10^{-6}	RADC, Thermocouple, Airborne	300	540	180
Switch Assembly	10/18/6	10×10^{-6}	Estimate	100	180	60
Setting Spring	10/18/6	2×10^{-6}	GIDEP (FARADA), Door Mechanism	20	36	12
Diaphragm	10/18/6	8×10^{-6}	GIDEP (FARADA), Pressure Diaphragm	80	144	48
Flex Hose	10/18/6	10×10^{-6}	RADC, Hoses, General Airborne	100	180	60

TOTAL FAILURE RATE: λ = 1,610 2,890 970

MEAN TIME BETWEEN FAILURES: MTBF = 621 hr 346 hr 1,031 hr

TABLE B-II (Continued)

WEIGHT AND BALANCE — CONCEPT L				10-Wheel	18-Wheel	6-Wheel
COMPONENT	QUANTITY (N)	FAILURE RATE (λ)	SOURCE OF λ	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$
Transducers	10/18/6	120×10^{-6}	GIDEP (FARADA), Force Wheel Sensor	1,200	2,160	720
Electronics Unit	1	100×10^{-6}	MIL HDBK 217B Component Data	100	100	100
Indicator Unit	1	10×10^{-6}	GIDEP (FARADA), Autopilot Indicator	10	10	10
Current Transformers	10/18/6	0.3×10^{-6}	MIL HDBK 217B	—	—	—
			TOTAL FAILURE RATE: λ =	1,310	2,270	830
			MEAN TIME BETWEEN FAILURES: MTBF =	763 hr	441 hr	1,205 hr

WEIGHT AND BALANCE — CONCEPT M				10-Wheel	18-Wheel	6-Wheel
COMPONENT	QUANTITY (N)	FAILURE RATE (λ)	SOURCE OF λ	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$
Transducers	10/18/6	120×10^{-6}	GIDEP (FARADA). Force Wheel Sensor	1,200	2,160	720
Electronics Unit	1	300×10^{-6}	DC-10 Data — Weight and Balance Computer	300	300	300
Indicator Unit	1	10×10^{-6}	GIDEP (FARADA), Autopilot Indicator	10	10	10
Current Transformers	10/13/6	0.3×10^{-6}	MIL HDBK 217B	—	—	—
			TOTAL FAILURE RATE: λ =	1,510	2,470	1,030
			MEAN TIME BETWEEN FAILURES: MTBF =	662 hr	405 hr	971 hr

TABLE B-II (Continued)

WHEEL SPEED — CONCEPT N				10-Wheel	18-Wheel	6-Wheel
COMPONENT	QUANTITY (N)	FAILURE RATE (λ)	SOURCE OF λ	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$	$N\lambda(10^{-6})$
System Computer	1	150×10^{-6}	DC-10 Data	150	150	150
Display and Control Panel	1	5×10^{-6}	DC-10 Data	5	5	5
Wheel Speed Transducer*	10/18/6	15×10^{-6}	DC-10 Data	150*	270*	90*
			TOTAL FAILURE RATE: λ =	305 (155)	425 (155)	245 (155)
			MEAN TIME BETWEEN FAILURES: MTBF =	3,279 hr (6,452)	2,353 hr (6,452)	4,082 hr (6,452)

*Also used on aircraft for other subsystems. Therefore, not charged against Tire Pressure Indicating system for causing delays. For probability of delay and Q_D calculations, use values in parentheses.

TABLE B-II (Continued)

1.	MIL-HDBK-217	Reliability Prediction of Electronic Equipment, Military Handbook 217B, Notice 2, 17 March 1978.
2.	DC-10 Data	The Douglas Aircraft Company Reliability Data Bank of airline reported reliability data.
3.	GIDEP (FARADA)	Reliability-Maintainability (R-M) Data Summaries from the Government-Industry Data Exchange Program, GIDEP Operations Center, Corona, California updated periodically.
4.	Estimate	Failure rates based on engineering judgement of similar equipment.
5.	RADC	Nonelectronic Reliability Notebook, Rome Air Development Center, RADC-TR-75-22, January 1975.

TABLE B-III. FAILURE RATE DATA SOURCE REFERENCES

	Percent of TPI Failures Detected By:					Problem of False Warning Due to:		
			FAILURE INDICATED					
CONCEPT	DET. & ANNUN. IN COCKPIT (% DA)	UN-DET. IN COCKPIT (% U)	BITE (MTBUR) (% B)	ATP (MTBF) (% A)	NEVER (Op. Time of TPI) (% N)	FALSE WARNING (% FW)	TRANS. AND INTER. ($Q_{T\&I}$)	MON. WARN LIMITS (Q_{MWL})
D ANALOG PRESSURE	98	1.5	60	30	10	0.5	$\frac{1}{50,000}$	$\frac{1}{20,000}$
E ANALOG PRESSURE	95	3	60	30	0	2	$\frac{1}{50,000}$	$\frac{1}{20,000}$
F ANALOG PRESSURE	95	3	60	30	10	2	$\frac{1}{50,000}$	$\frac{1}{20,000}$
G ANALOG PRESSURE	80	13	60	30	10	7	$\frac{1}{50,000}$	$\frac{1}{15,000}$
H PRESSURE SWITCH	70	15	60	30	10	15	$\frac{1}{50,000}$	$\frac{1}{20,000}$
I DIFFERENTIAL VALVE	84	12	60	30	10	4	$\frac{1}{50,000}$	$\frac{1}{10,000}$
J PRESSURE SWITCH	70	15	60	30	10	15	$\frac{1}{50,000}$	$\frac{1}{15,000}$
K PRESSURE SWITCH	70	15	60	30	10	15	$\frac{1}{50,000}$	$\frac{1}{15,000}$
L WEIGHT AND BALANCE	85	10	60	30	10	5	$\frac{1}{50,000}$	$\frac{1}{5,000}$
M WEIGHT AND BALANCE	85	10	60	30	10	5	$\frac{1}{50,000}$	$\frac{1}{5,000}$
N WHEEL SPEED	87	8	60	30	10	5	$\frac{1}{50,000}$	$\frac{1}{5,000}$

NOTE: The following percent monitoring % DA, % U, % B, % A and % N are defined on page B-20, and % FW, $Q_{T\&I}$ and Q_{MWL} are defined on page B-22.

TABLE B-IV. SUMMARY BY CONCEPT OF FACTORS AND TERMS USED IN CALCULATIONS

detected failures and could be in the equipment for a length of time up to the operating life of the aircraft, as indicated by the graph in figure B-2 for t_{op}.

B. Safety Study

Safety analyses were performed to estimate:

1. The probability of the system not operating properly during takeoff when a low tire exists, and

2. The probability of false warnings on takeoff.

The first situation could result in a hazardous condition similar to that which can occur today operating without a TPI system. The second situation could present a hazard, unique to operating with a TPI system, if the false low tire pressure warning occurred during takeoff roll and caused the pilot to initiate an unnecessary rejected takeoff. The safety calculations use the same data, where applicable, that are used in the reliability analyses. In addition, the safety calculations include the probability of a low/flat tire occurring per departure, for 6, 10, and 18 wheel aircraft. The probabilities, given for Q_T in paragraph II-B.1 below, are based on an extensive review of blown main tire incidents given in Appendix A for the time period from July 1974 through September 1976 for the DC-10, L-1011, B-747, B-707, B-727, B-737, DC-8, and DC-9 aircraft. During this period there were 234 incidents that could have been caused by low/flat tires in 1,178,169 departures for a 10 wheel aircraft, and 99 and 160 incidents in 123,903 and 3,325,035 departures for 18 wheel and 6 wheel aircraft, respectively. Low/flat tires during rollout and taxi-in after flights are not included because a review of the history of tire problems shows that taxi-out and takeoff are the hazardous phases for low/flat tires. Also, one-half of the incidents due to blown tires was considered to have been caused by low/flat tires and the other half due to other causes such as thrown treads.

The percent of the total TPI system failure rate that can cause false warnings, $\%_{FW}$, is also used in the safety calculations, paragraph II-B.2 below. The $\%_{FW}$ values are shown in Table IV and are based on engineering judgements since no data is available

for the portion of the failures of each concept that would erroneously annunciate to the flight crew a low/flat tire indication.

II. RELIABILITY AND SAFETY CALCULATIONS (Typical)

The equations used in the reliability and safety calculations and examples of the calculations, based on the TPI system of concept E for a 10 wheel aircraft are given below.

A. Reliability Calculations

1. TPI system operating properly during taxi-out and takeoff run.

The probability of the TPI system operating properly per departure, R_{TPI}, i.e. that it will detect and annunciate a low/flat tire to the flight crew from power on the aircraft through taxi-out and takeoff run is:

$$R_{TPI} = R_{DA} \times R_U \qquad (1)$$

Where: R_{DA} = Probability of the parts of the TPI system, whose failure is detected and annunciated in the cockpit, working properly.

R_U = Probability of the parts of the TPI system, whose failure is not detected and annunciated in the cockpit, working properly.

Considering the degree of monitoring and the percent of the hardware that is tested/checked, as shown in Table B-IV, R_{DA} and R_U can be written as

$$R_{DA} = e^{-(\lambda_{TPI} \cdot \%_{DA})t_{EXP}}$$

and

$$R_U = e^{-(\lambda_{TPI} \%_U)(\%_B \cdot t_B + \%_A \cdot t_A + \%_N \cdot t_{OP})}$$

so that R_{TPI} can be expressed as

$$R_{TPI} = e^{-\lambda_{TPI}[\%_{DA} \cdot t_{EXP} + \%_U(\%_B \cdot t_B + \%_A \cdot t_A + \%_N \cdot t_{OP})]} \qquad (2)$$

Where: λ_{TPI} = The total failure rate for the TPI system.

$\%_{DA}$ = Percent of the total TPI system failure rate that is detected and annunciated to the flight crew when the failure occurs.

t_{EXP} = Exposure time of concern during which the TPI system should be operating properly, in this case from power on through taxi-out.

$\%_{U}$ = Percent of the total TPI system failure rate that is undetected, i.e. due to failures in the TPI system that are not detected and annunciated to the flight crew when these failures occur.

$\%_{B}$ = Percent of the undetected TPI system failure rate that is checked for proper/improper operation during a BITE test of the TPI system.

t_{B} = Mean-Time-Between-Unscheduled-Removals (MTBUR) when a BITE test is performed and any existing B type failure of the TPI system is detected.

$\%_{A}$ = Percent of the undetected TPI system failure rate that is checked for proper/improper operation during an Acceptance Test Procedure (ATP). This is the percent that is in addition to $\%_{B}$.

t_{A} = Mean-Time-Between-Failures (MTBF) when an ATP test is performed and any existing A type failure is detected.

$\%_{N}$ = Percent of the undetected failure rate that is never detected, i.e. undetected failures that are not detected by either BITE or ATP tests.

t_{OP} = Total operating time of TPI system, since N type failures could occur any time during the operating time of the TPI system

without being detected or indicated by any tests.

NOTE: In the equation, percents (%) are shown, whereas in the calculations values are expressed as decimal numerics. All time and failure rate values are normalized in hours.

Thus the probability of the TPI system operating properly from power on through taxi-out and takeoff, R_{TPI}, can be determined from Equation (2) and using the appropriate data in Table B-II and IV. For example, for TPI Concept E, R_{TPI} would be, for a conservative average exposure time, t_{EXP}, of 20 minutes from TPI system power on through taxi and the takeoff run:

$$R_{TPI} = e^{-1,330 \times 10^{-6} \left[0.95 \cdot \frac{20}{60} + 0.03(0.60 \cdot 500^{*} + 0.30 \cdot 750^{*} + 0.10 t_{OP})\right]}$$

$$= 0.98\, e^{-4 \times 10^{-6} \cdot t_{OP}} \text{ (per departure)}$$

Since R_{TPI} varies with the operating time of the TPI system, Figure B-2 has been prepared to show the values of R_{TPI} versus operating time, t_{OP}, for Concept E.

Thus the value of R_{TPI} varies from 0.98 to 0.66 for zero percent "never detected" undetected failures to the worst case for the last departure in the life of the aircraft of 100,000 operating hours, respectively.

It should be observed that the value of R_{TPI} = 0.66 represents a worst case situation because the "never detected" failures might actually be discovered, if they occur, before 100,000 operating hours. This is possible in the event a low/flat tire occurs and the TPI system does not annunciate that condition. The TPI system would be 'squawked' and the system checked to determine why the system did not function properly. If a "never detected" failure was the cause, the tests/checks that would be performed would not locate the failure and the system equipment would check 'ok'. However, if another similar event occurred and the TPI system checked 'ok', the system might be subjected to a complete test of all the parts and the "never detected" failure discovered. However, the TPI system might not be subjected

*See *MTBUR on page B-24.

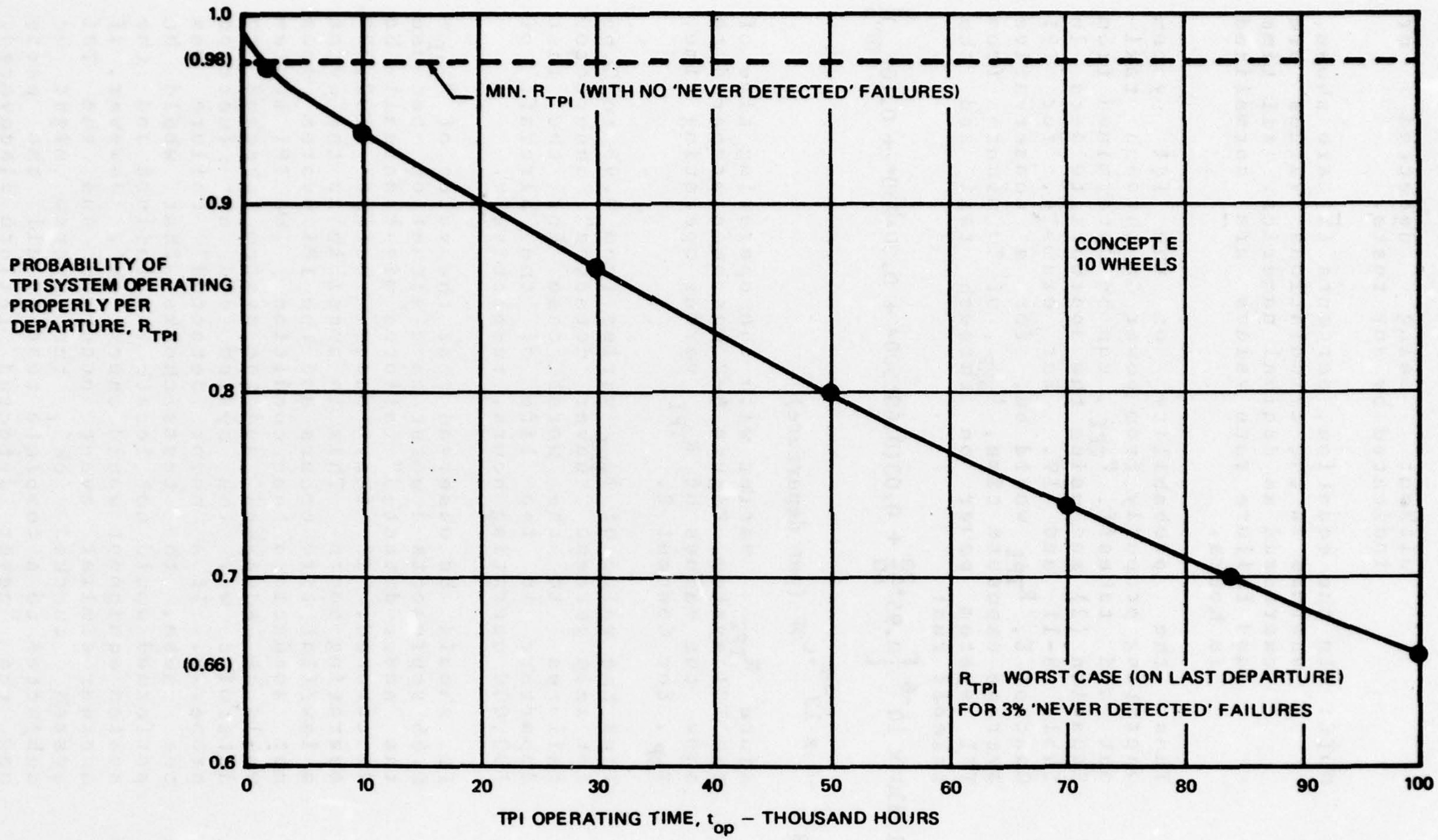


FIGURE B-2. PROBABILITY OF TPI SYSTEM OPERATING PROPERLY VERSUS TOTAL TPI SYSTEM OPERATING TIME

to a complete test until after more than three or more such events. Also, there is a probability that more than one "never detected" failure occurred in the system and the complete test of the system stopped after one "never detected" failure was found. The system could be repaired and placed back in service with another "never detected" failure still existing in the system. Thus, although it is likely that a "never detected" undetected failure would be discovered before the full 100,000 operating hours, it is difficult to say when, on the average, such a failure would be discovered and it is likely that a "never detected" failure could exist in the system for a very long period of time.

Also, if the system is occasionally called on to function due to one or more low/flat tires, and it functions properly, this constitutes a verification that a "never detected" failure has not occurred, at least on the affected wheel, and thus the exposure time t_{OP} for those elements begins anew each time they are successfully used. Accordingly, the curve for R_{TPI} in Figure B-2 is a function of this unknown time and is shown to the worst case operating time of 100,000 hours.

2. Delay Rate Caused by TPI System Failures

The probability of a delay caused by TPI system failures, Q_D, would be per departure:

$$Q_D = 1 - e^{-\lambda_{TPI}(\%_D + \%_{FW})t_{EXP}} + Q_{T\&I} + Q_{MWL} \qquad (3)$$

Where: $\%_{FW}$ = Percent of the total TPI system failure rate that falsely annunciates a low/flat tire warning in the cockpit.

$Q_{T\&I}$ = Probability per departure of TPI system falsely annunciating a low/flat tire warning in the cockpit due to transients and intermittents (non-hardware failure).

Q_{MWL} = Probability per departure of TPI system falsely annunciating a low.flat tire warning in the

cockpit due to the TPI monitor limits being exceeded when no low/flat tire exists (non-hardware failure).

*MTBUR = 500 hours is obtained by dividing the MTBF (750 hours for Concept E from Table B-I) by 1.5, as discribed in paragraph I above; ref. p.B21.

and the delay rate for TPI system failures, DR_{TPI}, per 10,000 departures would be:

$$DR_{TPI} = Q_D \times 10{,}000$$

For TPI system Concept E the delay rate would be, using data from Tables B-II and IV and for an average exposure time of 20 minutes from TPI system power on through taxi-out to the runway:

$$Q_D = 1 - e^{-1{,}330 \times 10^{-6}\,(0.95 + 0.02)\,\frac{20}{60}} + \frac{1}{50{,}000} + \frac{1}{5{,}000}$$

$$= 4.3 \times 10^{-4} + 0.2 \times 10^{-4} + 2 \times 10^{-4} = 6.5 \times 10^{-4} \text{ per departure}$$

and, DR_{TPI} = 6.5 delays per 10,000 departures due to TPI system failures.

B. Safety Calculations

1. Hazard Due to a Low/Flat Tire and Lack of Warning During Takeoff

The probability per departure, Q_{HAZ}, of a hazard due to a low/flat tire and lack of warning during takeoff can be expressed as the probability per departure that the TPI system will not operate properly (not warn) for a low/flat tire during taxi and during the takeoff run, Q_{TPI}, combined with the probability that a low/flat tire exists, Q_T, is:

$$Q_{HAZ} = Q_T \times Q_{TPI}$$

Where: Q_T = Probability per departure that a low/flat tire exists = 2.4×10^{-4} for a 10 wheel aircraft. The probabilities of a low/flat tire for 18 wheel and 6 wheel aircraft

are 3.0×10^{-4} and 4.8×10^{-5}, respectively.

$Q_{TPI} = 1 - R_{TPI}$ refer to relationship shown in paragraph I above.

Thus:

$$Q_{HAZ} = Q_T \cdot (1 - R_{TPI})$$

For Concept E (10 wheel aircraft) using values in Tables B-II and IV and an exposure time, t_{EXP}, equal to taxi-out time plus takeoff time of 20 minutes together with a probability, Q_T, that a low/flat tire exists of 2.4×10^{-4} given above, results in values of

$$Q_{HAZ} = 2.4 \times 10^{-4} (1 - 0.98)$$
$$= 0.5 \times 10^{-5} \text{ or } \frac{1}{200,000}$$

Takeoffs for zero percent "never detected" undetected failures and

$$Q_{HAZ} = 2.4 \times 10^{-4} (1 - 0.66)$$
$$= 8.2 \times 10^{-5} \text{ or } \frac{1}{12,195}$$

Takeoffs for 3 percent "never detected" failures which is the worst case value for Q_{HAZ} for the last departure in the lifetime of the aircraft (100,000 operating hours).

2. Probability of a False Warning During Takeoff

The probability per departure of a failure of the TPI system so that a false warning to the flight crew occurs during the critical portion of the takeoff run is:

$$Q_{FW} = 1 - e^{-\lambda_{TPI} \cdot \%_{FW} \cdot t_{TO}}$$

Where: $\%_{FW}$ = Percent of the total TPI system failure rate that cause false warnings, i.e. erroneously annunciates to the flight crew a low/flat tire indication.

t_{TO} = Critical takeoff period = 30 seconds.

Accordingly, the value of Q_{FW} for Concept E (10 wheel aircraft) based on the data in Tables B-II and IV is:

$$Q_{FW} = 1 - e^{-1,330 \times 10^{-6} \times 0.02 \times \frac{30}{3600}}$$

$$= 2.2 \times 10^{-7} \text{ or } \frac{1}{4,545,454} \text{ takeoffs}$$

III. RELIABILITY AND SAFETY SUMMARY

The values for Reliability - an estimate of the Mean-Time-Between-Failures (MTBF), the probability of the TPI system operating properly during taxi-out and takeoff (R_{TPI}), and the probability of a dispatch delay - and also the values for Safety - the probability of the TPI system not operating properly during takeoff when a low/flat tire exists (Q_{HAZ}), and the probability of a false warning on takeoff (Q_{FW}) - are summarized in Table B-I. The summary includes Concepts E through V for 10, 6, and 18 wheel aircraft. Values of R_{TPI} and Q_{HAZ} are shown for 3 percent and for zero percent "never detected" undetected failures so that the magnitude of improvement in reliability and safety can be seen by eliminating all "never detected" failures, i.e. by assuring that all circuitry/parts of the TPI system are tested during an Acceptance Test Procedure bench check.